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OPTIMIZATION AND IMPLEMENTATION OF WATER HEATER IN HOME ENERGY MANAGEMENT SYSTEM

Master of Science thesis

Examiner: Prof. Sami Repo
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ABSTRACT

YIK CHEN Sii: Implementation and Optimization of Water Heater in Home Energy Management System
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The purpose of this thesis is to analyze the water heater as an electric space heating in home energy management system using the newly installed water heater system in microgrid laboratory. The rise of decentralized power production from renewable energy sources and uncertainty in weather forecast induce the need to have controllable thermal loads such as water heater. This thesis focused on finding the time and water temperature relationship experimentally and integrating the water heater system to home energy management system.

In the microgrid laboratory, a water heater system, consisting of a 1.8 kW water heater that has a capacity of 29 liters, two Pt500 resistance thermometers, an energy meter that displays water temperatures and volumetric flow rate, an air cooling system, a water pump and minimal hoses, is used to emulate real-life residential space heating behavior. A number of experiments are conducted to measure the water temperatures during heating and cooling period. The relationship between time and temperature is approximated using Least Squares Fitting method. The time to heat the water from 20.8ºC to 55ºC is around 70 minutes while the cooling time is around 8 hours.

With those approximated solutions, the accuracy is further verified by alternating the heating and cooling sequences in different amount of time, such as 10 minutes, 15 minutes 20 minutes and 30 minutes. The comparison between calculated and measured water temperatures confirms that it is possible to calculate the water temperature based on the approximated solutions.

The water temperatures are then extrapolated to 80ºC for heating to find out the heat demand the air cooling system is able to provide. The integration of the approximated solution to the production following algorithm or HEMS shows that a redesign of HEMS is necessary in order to include water temperature as a new input for the algorithm. Furthermore, the communication of the water heater system to an external device using M-Bus communication protocol is documented.

PREFACE

I would like to thank Prof. Sami Repo for dedicating the time and effort to supervise me during my exchange semester in Tampere University of Technology. The discussions we have had made me understand more about the energy industry in Finland and the challenges we face to integrate renewable energy into the power grid. Your words colored my life and made me a better human being.

I would also like to thank Jakub Esner and Antti Supponen for all the support and cheerful discussion in helping me to understand the microgrid laboratory. Special thanks to all other colleagues in Department of Electrical Engineering in showing me the unique Finnish culture and wonderful experiences in Tampere. And to Jaakko, for the words cannot justify my appreciation of all the help you gave.

Lastly, I would like to express my eternal gratitude to Jing Ying and my family, who are always behind my back and believe in me. It is wonderful to have you in my life.

"*Vision without action is merely a dream. Action without vision just passes the time. Vision with action can change the world*."

Erlangen, 10.6.2017

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LIST OF SYMBOLS AND ABBREVIATIONS

ADS	Active Distribution System
AMR	Automatic Meter Reading
CHP	Combined Heat and Power
COTS	Commercial off the Shelf
DER	Distributed Energy Resources
DG	Distributive Generation
DSM	Demand Side Management
DR	Demand Respond
EMS	Energy Management System
ESS	Energy Storage System
HEMS	Home Energy Management System
HVAC	Heating, Ventilating and Air Conditioning
MPP	Maximum Power Point
PCC	Point of Common Coupling
PV	Photovoltaic
VPP	Virtual Power Plant
CO_2	Carbon dioxide

c_w	specific heat capacity of water
m	mass
P	power
Q	heat energy
$Tinlet$	Temperature of water upon entering water heater
$Toutlet$	Temperature of water after leaving water heater
V	volume

1. INTRODUCTION

Renewable energy has been gaining traction lately as the awareness of the need to have green and sustainable energy raises rapidly not only among the developed nations, but also China and India. In early 2017, China announced that they would spend 2.5 trillion yuan (€330 billion) into renewable energy generation by 2020[1] while India plans to have 60% of its power production come from non-fossil fuel resources by 2027[2]. Finland has set the goal of meeting 38% of its energy consumption from renewable source by 2020 (International Energy Agency 2013). Greenhouse gases like carbon dioxide (CO_2) are released into Earth's atmosphere by the burning of fossil fuels such as coal, petroleum and natural gas. In the energy sector, burning of fossil fuels is used traditionally in centralized power station to produce electricity. There are numerous reports indicating that the increase of greenhouse concentration in the Earth's atmosphere causes global warming and rising sea level. On the positive note, Sweden's national policy to charge heavy carbon taxes has seen the nation reducing its carbon emission by 9% from 1990 to 2006[3]. The move to shut down all nuclear power stations by 2022 from Germany's federal government through its energy transition program *Energiewende* is catalyzed since the Fukushima Daiichi nuclear disaster in 2011. Recently, a key milestone was reached in Paris in December 2015 when 192 countries around the globe set a goal of limiting the global warming to 1.5 degree Celsius compared to pre-industrial levels.

Renewable energy resources rely heavily on favorable weather condition, rendering their ability to be reliable and available throughout the days and different seasons. A major storm outbreak named Cyclone Gudrun in Denmark on 8th January 2005 caused the nation to lose about 90% of its energy production from wind turbines for a period of 8 hours (Haanpää et al. 2007). Rainy or cloudy days could hamper the efficiency of photovoltaic (PV) panels. In Norway, 99% of its electricity comes from hydropower but it is vulnerable to drought year. Germany has plenty of wind energy in the northern side, but the industries are residing in the southern side. In Finland, nuclear reactor is favored due to its ability to generate constant energy. However, power has to be imported from neighboring countries during peak hour, as Finland does not have enough power production capacity to meet the peak load conditions. An energy storage system (ESS) that could store large amount of energy harnessed from renewable resources and discharge it quickly based on

[1] China to plow $361 billion into renewable fuel by 2020, www.reuters.com, 25.01.2017
[2] India plans nearly 60% of electricity capacity from non-fossil fuels by 2027, www.theguardian.com, 22.12.2016
[3] Sweden's carbon-tax solution to climate change puts it top of green list, www.theguardian.com, 29.04.2008

the load demand could be a viable solution to increasing the reliability of renewable resources in the near future.

European Union (EU) has set three targets by 2020[4] related to energy and emission reduction. These 20-20-20 targets are reduction of greenhouse gas emission by at least 20% below the level in 1990; reduction of primary energy usage by 20% by means of improving energy efficiency and making renewable resources account for 20% of total energy consumption. This laid the foundation and investment for the future of power generation. As more distributed energy resources (DER) emerge in the market, the need to decentralize existing power grid infrastructure and facilitate information exchange becomes essential. In order to increase energy efficiency from end-consumer's point-of-view, it is important to know the energy consumption pattern. Consumption pattern varies among individuals but the main factors that influence energy consumption include the size and type of residential building, the amount of people living in the building and the location or weather condition of that geographical area.

Hot water plays a major role in Finnish household. In Finland, space heating accounts for 66% of energy consumption in a household as depicted in Fig. 1 below. Space heating refers to the heat to keep the residential and free-time buildings warm. This implies that there is a strong dependency on hot water in Finland especially due to its long winter and cold climate behavior. Domestic hot water represents the hot water coming out from the tap typically for shower and dishwashing. It is worth noticing that a common water heater can provide hot water for both space heating system and domestic hot water system as long as both water systems do not mix up, which means both systems can use hot water from the same source but it is preferable not to mix up the water due to hygienic concern. There are two opposing risks concerning the water temperature inside domestic water heater; risk of scalding and risk of being exposed to Legionella, a bacteria responsible for the Legionnaires' disease[5]. The former risk occurs when water temperature exceeds 49ºC while the bacteria favors water temperature between 32ºC and 35ºC for growth. There is no growth above 55ºC and a temperature of over 60ºC has a bactericidal effect. Thus, risk of getting Legionnaires' disease by consuming hot water can be prevented when the water is heated over 60ºC.

[4] Climate Action - 2020 climate and energy package, www.ec.europa.eu/clima/policies/strategies/2020
[5] Guidelines for Drinking Water, World Health Organisation (WHO)

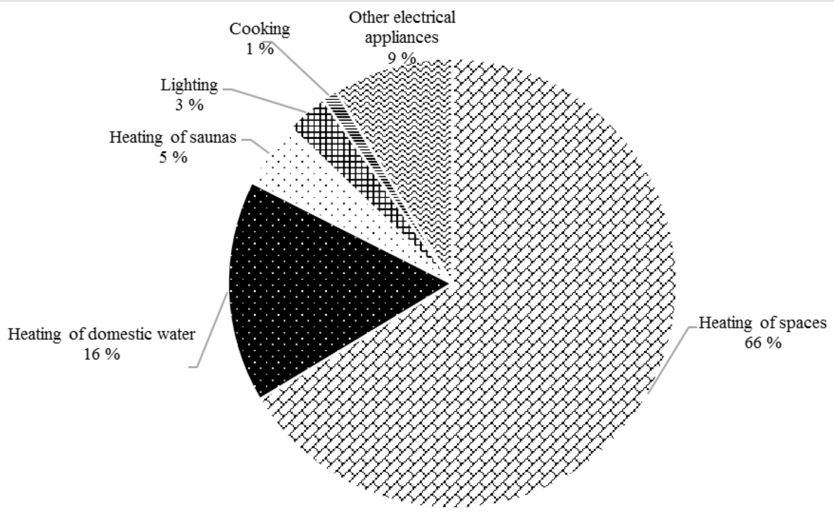

***Figure 1. Energy consumption in Finnish households by use in 2015*[6]**

Household appliances including lighting, cooking and other electrical equipment account for 13% of the energy consumed. It can be seen in**Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.** Figure 1 that space heating consumes the most energy in a household. The detailed information is further stated in Table 1 below. The energy usage is greatly dependent on the weather condition. The decreasing trend in energy consumption from 2010 to 2015 as seen in Table 1 is due to warmer weather, whereas in February 2012 there was an exception in which extremely cold weather hit Finland and thus increased the energy consumption in space heating[7].

Table 1. Energy consumption in households by use from 2010 to 2015 in GWh

	2010	2011	2012	2013	2014	2015
Heating of spaces	48 765	41 419	45 928	42 739	42 831	40 804
Household appliances	9 092	8 320	8 856	8 395	8 099	7 886
Heating of saunas	2 880	2 871	2 894	2 902	2 924	2 920
Heating of domestic water	9 522	9 584	9 658	9 727	9 789	9 850
Housing, total	**70 259**	**62 194**	**67 336**	**63 763**	**63 643**	**61 460**

By looking further at the energy consumption by energy source in Table 2, space heating with electricity contributes to about 23.2% of the total energy used in space heating[8]. In this category, the application that uses electricity as the source for space heating includes direct electricity heating, electric storage heating, additional heating, floor heating by

[6] Statistic Finland, www.stat.fi/til/asen/2015/asen_2015_2016-11-18_tau_001_en.html
[7] Statistic Finland, http://www.stat.fi/til/asen/2013/asen_2013_2014-11-14_tie_001_en.html
[8] Statistic Finland, http://www.stat.fi/til/asen/2015/asen_2015_2016-11-18_tau_002_en.html

electricity, electricity used by heat pumps and lastly electricity consumed by heating systems and heat distribution equipment. While being the third most used source for space heating, electricity is readily available in the household and there is no requirement for signing extra contract to procure heat energy from for example, district heating.

The main source for space heating comes from district heating, in which the heat is generated in a centralized location and then distributed to the neighboring area. It is the most popular source for space heating as it is centrally controlled and people will have less worry about potential technical issues or breakdowns. Ambient energy refers to the thermal energy collected from the air or the ground outside which is generated from heat pumps. The heat energy from a lower temperature source is moved to a warmer destination in a process called reversed heat engine.

Table 2. Energy consumption in households by energy source in 2015 in GWh

	Heating of spaces	Household appliances	Heating of saunas	Heating of domestic water	Housing, total
Wood	11 630	-	1 805	465	13 900
Peat	28	-	-	15	43
Coal	3	-	-	1	3
Heavy fuel oil	57	-	-	25	82
Light fuel oil	2 926	-	-	742	3 668
Natural gas	235	107	-	65	407
Ambient energy	3 711	-	-	754	4 465
District heat	12 750	-	-	5 226	17 976
Electricity	9 464	7 780	1 115	2 558	20 917
Total	**40 804**	**7 886**	**2 920**	**9 850**	**61 460**

1.1 Motivation

Microgrid is a local cluster of smaller-scaled power generations, storage systems and loads that are interconnected to one another, enabling local energy production and consumption according to the need. Renewable energy resources are strongly weather dependent and this poses a challenge to maintaining a steady supply of energy whole day long. Microgrid is connected to the power grid and could operate either by drawing energy from the grid or supplying energy to the grid. The main advantage of microgrid is that it could function also in islanding mode, meaning that it could work independent of the central power grid. This ensures that the huge fluctuation in energy production would not affect the central power grid. Traditionally, small and autonomous grids have existed for many years in remote areas where it is not feasible to connect those remote areas to the main power grid either economically or technically. Microgrid is seen as a flexible and reliable way of integrating new distributed generation to the existing central grids. A lot of researches have been carried out to study its feasibility in energy production (Hatziargyriou et al., 2007).

Water heater is readily available in the market and has been one of the most common item to have in every household. Its relatively inexpensive purchasing and lower maintenance cost are clear financial benefits over Battery Energy Storage System (BESS) such as lithium ion battery. While water heater cannot convert the heat energy it stored previously into electricity, using this passive energy storage system intelligently could help to reduce the cost of usage for end-consumers and increase the flexibility of maintaining the balance of load demand and electricity supply for utility providers. The keywords here are intelligent and controlled heating. Intelligent heating refers to heating the water only at times when the electricity tariff is lower, which typically happens during off-peak hour; or when there is a production surplus from the renewable resources such as photovoltaic panels. The technical issue in intelligent heating lies on the control algorithm, a topic which will be detailed in this thesis. Meanwhile, controlled heating represents a heating sequence that can be scheduled and monitored from a control system and is determined with the variables like water temperature and house indoor temperature.

As the world's population continues to grow and the amount of greenhouse gases rises in the atmosphere, the need to have clean energy becomes a major concern. The decision to switch from traditional way of obtaining electricity by burning fossil fuel to generating electricity from renewable energy resources concerns not only the economic and technical factors, but also political factors such as the current regulation and taxation. Alternatively, the improvement for energy efficiency can also help to tackle the problem of meeting the increasing demand for clean and affordable energy. Energy efficiency could be achieved technically or from bottom-up, when people start to conserve electricity and reduce the energy consumption.

1.2 Approach and scope of thesis

The Microgrid Laboratory in Department of Electrical Engineering in Tampere University of Technology has installed a water heater system as a controllable load, with the goal of connecting and integrating it to Home Energy Management System (HEMS). This thesis is separated into two major parts; the first part focuses on implementation of the water heater in Microgrid Laboratory while the second part of the thesis studies the optimization potential of the water heater system and HEMS. In the first part, communication between water heater system and HEMS is studied. There is no information exchange between them yet and one of the targets for this thesis is to document the related information regarding the communication protocol used by water heater system. The ultimate goal would be to fully integrate water heater system into HEMS or to allow information exchange between each components in the microgrid. In the second part, optimization of water heater includes documentation of the factors that could improve the functionality of HEMS. Additionally, measurements of the water temperatures are carried out to investigate the rate of heating and cooling of the water heater system, with the hope of simplifying the algorithm used in HEMS to calculate the water temperature. The temperatures can be used as controlled variables for HEMS, which in turn would turn on the water heater or off according to different heating strategies. The measurements are in accordance with the work in *Lehrstuhl für Fertigungsmesstechnik* or Chair of Manufacturing Metrology at Friedrich-Alexander University of Erlangen-Nuremberg. The following summarizes the content of each chapter in this thesis.

Chapter 1: Introduction of current energy market trend and motivation for the thesis. Approach of how the thesis is conducted is presented

Chapter 2: Overview of microgrid and its control strategies. The microgrid laboratory is introduced

Chapter 3: Implementation part of the thesis where the components of water heater system are documented. Communication protocol between the energy meter and external computers is documented

Chapter 4: Optimization part of the thesis where the factors affecting the control of water heater are discussed

Chapter 5: Experimental part of the thesis where the Least Squares Fitting method is used to approximate the relation of time and water temperature. Verification of the solutions with interrupted heating time is done and the heat demand that can be provided by the water heater is calculated

Chapter 6: Conclusion and future work recommendation

2. BACKGROUND

2.1 Microgrid

Microgrid is a localized electric grid that can operate autonomously. It usually includes a combination of power generation sources, loads and storage devices that can be centrally controlled. Figure 2 below shows an example of microgrid. The power generation occurs from renewable energy resources such as PV panels or wind turbines. They are weather dependent and thus are considered as non-controllable generation in the figure below. Controllable generation might include Combined heat and power (CHP) which produces power and heat simultaneously by utilizing the heat waste from power generation to warm out buildings. There is a backup power generation typically in the form of diesel generator that will be switched on in case of production shortage. Additionally, controllable loads come from residential or commercial buildings and they include water heaters or air-conditioners. Energy storage stores the excess production from non-controllable generation or when the price of electricity is lower, usually during off-peak hour.

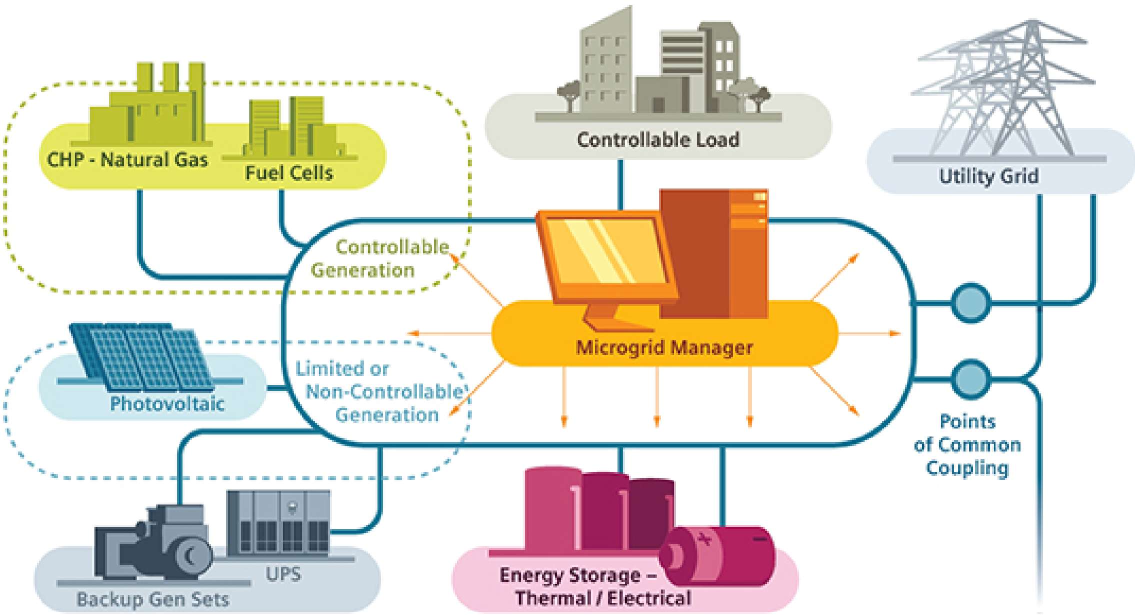

Figure 2. Example of microgrid[9]

The microgrid manager acts as a centralized controller that connects all generations, loads and energy storages and allows those components to function autonomously by integrating and optimizing power generation with the controllable loads. Microgrid is connected to the centralized power grid at distribution level at a single point of connection, which is known as the point of common coupling (PCC). PCC allows microgrid to function either

[9] Picture from Siemens Microgrids, http://w3.usa.siemens.com/smartgrid/us/en/microgrid/pages/microgrids.aspx

in grid-connected mode or stand-alone mode, in which the PCC is switched off and microgrid functions fully on its localized electric grid. Microgrid can thus operate in both modes and handle the transition between each mode. In case of power deficit within the microgrid, power can be injected from host grid through PCC. Excess in power production within the microgrid can be traded to the host grid in exchange with ancillary services such as incentives or subsidies. In stand-alone mode, real and reactive power are generated within the microgrid and a constant balance between power supply and demand is crucial. This flexible feature allows the integration of distributive generation (DG) into the centralized power grid. DG can be smaller-scaled decentralized generation or storage that could be produced from renewable energy sources. As it becomes more economical and environmental to generate electricity from renewable energy sources, microgrid is seen as a feasible solution to integrate DG to the host grid.

Currently, Smart Grid is a hot research topic in the field of electrical engineering. It is an upgrade to the traditional unidirectional power grids and supports bidirectional flow of power and information in order to create an automated, connected and distributed network of energy system (Fang et al., 2012). Microgrid and its several evolved forms, such as Active Distribution System (ADS), cognitive microgrid and Virtual Power Plant (VPP), can be utilized and served as the main platform for Smart Grid (Morais et al., 2008, Pudjianto et al., 2008, Ruiz et al., 2009).

Part of the thesis is to give an overview to microgrid controls. To understand how the control works, some basic challenges in microgrid are presented below. There are a few operational challenges concerning microgrid as seen in (Olivares et al., 2014). The most relevant challenges are:

1. Bidirectional power flow could cause reversed power flow at low voltage (LV) level
2. Stability issues regarding the transition of grid-connected mode to stand-alone mode
3. New approach and assumptions to model microgrid at transmission level
4. Proper control mechanism to deal with low inertia in microgrid which could lead to frequency deviation in stand-alone mode
5. Uncertainties in weather forecast poses a challenge to operate microgrid economically and reliably especially in stand-alone mode.

The controls in microgrid are briefly presented below. The technical details for the controls are mentioned in (Olivares et al., 2014).

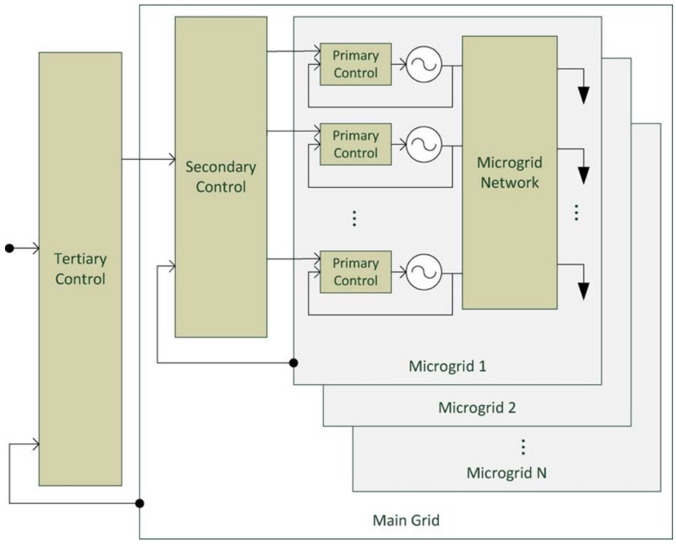

Figure 3. Hierarchical control levels: primary, secondary and tertiary control

There are three levels of hierarchical control in microgrid. They are primary control, secondary control and tertiary control as illustrated in Figure 3. The primary control, or local control is the first level in the hierarchy and relies almost solely on local measurement and no communication is needed. It provides the fastest response as a result and other controls such as islanding detection, output control and power sharing control fall on this level (Katiraei et al., 2005). The secondary control ensures reliable, economical and secure operation of the microgrid in both grid connected-mode and stand-alone mode. It is also known as microgrid Energy Management System (EMS). Secondary control operates in a slower response than primary control as more time is allocated for complex calculation. Tertiary control is the highest level in the hierarchy and it usually controls a few microgrids. It sets long-term set points and fulfills the requirements such as voltage support and frequency regulation based on the host grid. There are several state-of-the-art techniques used in primary control:

1. Primary control
    a. Inverter Output Control
    b. Power Sharing Control
        i. Droop-Based Methods
        ii. Non-droop-based Methods
2. Secondary control
    a. Centralized approach
        i. Optimal Dispatch
        ii. Bidding
        iii. Non-Model-Based Approach
        iv. Energy Storage System (ESS) Considerations
        v. Model Predictive Control
        vi. Communications
    b. Decentralized Approach using Multi-Agent System approach
3. Tertiary control

The details for each level of control are not further discussed in this thesis. More information regarding the technical details of the trends in microgrid control can be found in (Olivares et al., 2014).

2.2 Microgrid Laboratory

The microgrid laboratory in the Department of Electrical Engineering in Tampere University of Technology was first developed in (Esner, 2014) in order to provide a realistic testing environment for residential power consumption. It is illustrated in Figure 4 below. There are seven three-phased channels which can be connected to different generations, loads or energy storages. This setup emulates a real microgrid environment as discussed previously. There are two rows of contactors mounted in the microgrid, with the ability to switch on or switch off the channel. The bottom row of contactors is controlled by dSpace computer while the top row of contactors is controlled wirelessly using Z-Wave by HEMS computer. dSpace computer is able to measure the voltage, current and power of each channel and implement the consumption pattern in a residential building by alternating the contactors. HEMS computer is set to be the microgrid manager acting as a central control and a communication hub between the generations, loads and energy storages. Information exchange will take place within HEMS computer which acts like a gateway between all the components in microgrid. The challenge here is to have a uniform communication protocol and different communication protocols will ultimately be translated into one single protocol such as IEC61850.

Figure 4. Microgrid laboratory environment

It is aimed that HEMS computer will collect information such as weather forecast, day-ahead pricing of the electricity and energy demand forecast to optimize power generation with the controllable loads and energy storage. This will allow the microgrid to operate autonomously. For this to happen, control strategy in the microgrid plays a major role. There are numerous control strategies which are being studied and in the next section, the trend in control strategy has been mentioned briefly in the previous section.

The newly installed water heater system is connected to one of the seven three-phased channels in Microgrid Laboratory, which provides power to the water heater system to operate. Besides the water heater system, a PV inverter, a battery energy storage system and some resistive loads will be connected to the Microgrid Laboratory in the future. Water heater system will be acting as a controllable thermal load. More details about the water heater system will be discussed in the next chapter.

At the moment, residential behavior is emulated by dSpace, a control unit that sends signal to control the bottom row of contactors for each channel. The control signals are generated from Matlab first in the form of decimal number and then converted to binary number such as 1010001 for a given timeframe. The decimal number for this example is 81. In this example, binary 1 tells the contactor to be closed, allowing current to go through the circuit. Reading from left to right, the example shows that channel 1, 3 and 7 are closed. The resistive loads that are connected to these channels will be turned on for a given amount of time. dSpace computer is connected to dSpace directly and these binary signals are generated directly from the dSpace computer. In order to switch on the water heater for any given amount of time, the decimal number for the correct sequence should be figured out first and used in the Matlab script in dSpace computer. Its respective binary number will allow the contactor to be closed.

HEMS computer has the ability to control the top row of contactors wirelessly using Z-Wave[10]. Z-Wave is a wireless communication protocol for home appliances such as lamps and other sensors and it is used primarily in Smart Home or home automation. To use Z-Wave, a USB stick from Aeon Labs is needed. Z-Wave is installed in HEMS computer and it can be used to close or open the contactors for each channel. Having similar functionality as compared to dSpace computer controlling the computer, HEMS computer converts decimal number to binary numbers too and this signal is sent from the USB transmitter to the receiver attached to the contactors. However, HEMS computer will use these controls as a central control like the microgrid manager rather than to emulate residential behavior. At the moment, the production following program developed in (Esner, 2014) schedules the power generation and controls the heating demand based on the electricity price from Elspot and weather condition estimation. Elspot is a market price for electricity in the Nordic and Baltic countries. The price varies every hour and is determined by the supply and demand curve.

[10] An Introduction to Z-Wave Programming in C#, www.digiWave.dk/en

3. IMPLEMENTATION

This chapter documents the components in the water heater system and summarizes the communication protocol required in water heater system. It uses M-Bus communication protocol to communicate with external devices such as computers. The components in water heater system are water heater, energy meter, air cooling system or radiator, control unit, thermometers and water pump. Figure 4 illustrates the water heater system. They are products of commercial off-the-shelf (COTS), meaning they can be easily procured and reproduced in the future.

3.1 Components of Water Heater System

Water heater system was installed by the laboratory engineers from Department of Electrical Engineering Lasse Söderlund and Pekka Nousiainen. It serves as a controllable load to be connected to the microgrid laboratory. It has two power connectors that could connect directly to the channels in microgrid laboratory. The Harting Han® E-Series industrial connector with 6 pins powers the water heater only and it is shown in Figure 5a while the 16A three-phase power connector is attached to the circuit breaker and responsible for the rest of the components. It is depicted in Figure 5b.

a.

b.

Figure 5a. Water heater power connector b. circuit breaker connector[11]

Both connectors are able to supply 16A of current and 230V of voltage. In the Microgrid Laboratory, the first two channels from the left are built with the red female connectors from Mennekes while the remaining five channels are those from Harting.

[11] Pictures from www.harting-usa.com and www.menekes.com respectively

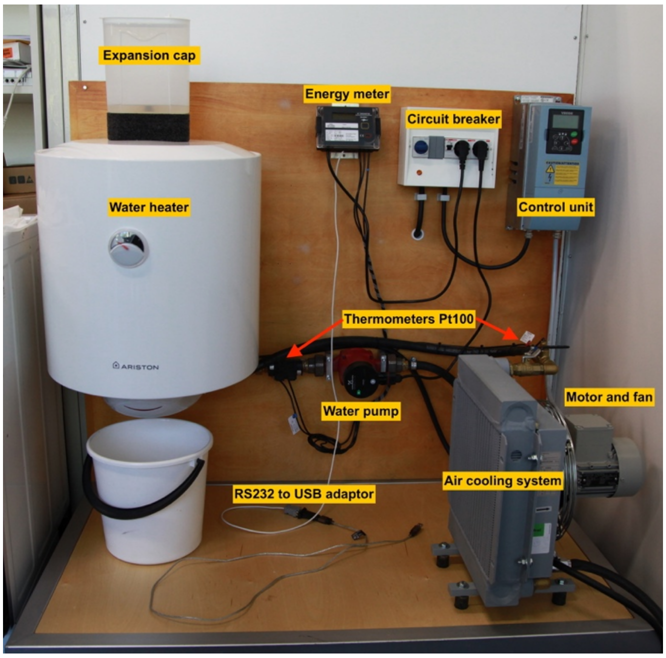

Figure 6. Water heater system

3.1.1 Water heater

The Ariston Pro R water heater for household holds a capacity of 29 liters. It is a single phase resistive heater with a rated power is 1.8 kW. A LED at the bottom of the tank signals power status while the round indicator in front of the tank shows the water temperature. It has three zones and in Figure 6 the indicator points at the room temperature at 20.8ºC. The heater has an internal thermostat with overheating protection at around 56ºC, meaning that the heater will turn off automatically when the water temperature reaches this maximum level. The indicator will rest exactly at the middle pointing upwards. An expansion cap is mounted above the water heater that allows the overflow of water as it is heated.

The water heater system is a closed-loop system, as there are no water coming out from the valve nor is there any additional water from the water tap. Water can be filled in through the expansion cap and removed by opening the drain valve located at the bottom of the water heater. This water heater is suitable for household usage and can be mounted on the wall.

The water heater has a good insulation, however, it is not known how thick the insulation is and what is the material of the insulation. Thus it is not possible to model the thermodynamic behavior of the water heater using mathematical equations. The mathematical equation to represent this multilayer structure of a water heater can be expressed by comparing it to electrical circuits, using electrical analogy as the foreground to explain the relationship of each layer of material in the water heater. In this approach, heat flow is regarded as electric current in the circuit; temperature is the electric potential; heat resistance and heat capacitance are similar to the electrical resistance and capacitance. Each layer inside the water heater has its own value for resistance and capacitance. The temperature gradient inside the water heater varies according to the distance of the resistive heating element. It is through convection that how water will be circulating upwards to the top of the water heater and cold water will move downwards as a result. For modelling purpose the water heater can be divided into different zone as seen in (Loga, 1991) and (Lutz, 1999). For the experiment part in this master thesis, the temperature inside the water heater is represented by the red thermometer measuring warmer water coming out of the water heater.

3.1.2 Energy meter

The Diehl Sharky 773 energy meter is a smart digital meter reader that not only shows the water temperature but also can calculate the energy consumption and billing information. In this water heater system, two thermometers and one flow meter are connected to the energy meter. The energy meter can read and display the information either on the screen or in external device. Figure 7 illustrates the energy meter. The only button in yellow color allows user navigate the displayed information and by pressing the button for longer than three seconds, the user can jump to different loops which shows more information such as water quantities and operating days. There are six loops in total; they are main loop, reading date loop, information loop, pulse input loop, tariff loop and month loop. User can define what kind of information to be displayed based on the software Hydro-Set which is a proprietary software from Diehl Metering.

Figure 7. Sharky 773 energy meter from Diehl Metering

The energy meter resembles an important interface for information exchange with the microgrid. It uses M-Bus protocol to communicate with external device and in this thesis, the protocol was extensively researched and it will be documented in the upcoming section.

The two thermometers here use Pt500 as the sensor to measure the water temperature. Pt500 is a type of platinum resistance thermometer, whose resistance changes with temperature gradient. Pt refers to the material Platinum while the value 500 shows that the sensor has a resistance of 500 Ohms at 0ºC. These thermometers in the laboratory can measure a range of temperature from 0ºC to 150ºC and the sensitivity for each temperature difference is 0.125K. The first thermometer measures the hotter water from water heater and has a red label on it. It is located right before the water enters the air cooling system. The other thermometer is positioned right after the water pump. The flow sensor is also mounted at similar position.

According to the installation guide in (Metering), the energy meter supports three types of communication channels; they are communication via radio, M-Bus communication module and RS232 communication module. Communication channel with RS232 communication module has been configured. RS232 is a serial interface that is most commonly used in the industrial communication. Due to limited RS232 ports from HEMS computer, a RS232-to-USB adaptor is used to connect the energy meter to external device. In the experiment part of this thesis, Hydro-Set software is used to get the temperature readings from the thermometers.

3.1.3 Hydro-Set Software

The software Hydro-Set is a proprietary software from Diehl Metering, the manufacturer of energy meter Sharky 773. It can be downloaded from the company's website[12]. Figure 7 illustrates the starting up of the software.

Before starting the software, the USB adaptor is connected to the HEMS computer and the water heater system is turned on to allow the readings of the water temperatures. The correct settings to read the information from energy meter is shown in Figure 7, where the section "COM 10" varies according to the actual port that is active in the computer. This can be checked in Control Panels in Windows 7, under Devices. While plugging in the USB, a new port number for COM will appear. Baud represents the speed in which bits are transported per second. This is common in serial communication which transfer bits by bits.

When the parameters are chosen, clicking the Read button will lead to fetching the data from energy meter. It takes approximately twenty seconds to fetch the data. User can also

[12] Diehl Metering website, http://www.diehl.com/de/diehl-metering/produkte-loesungen/produkt-download/anzeige-nach-produktfamilien.html

save the data or load previously saved data. The interesting information used in this thesis is Flow Temperature, Return Temperature and Volume Flow as shown in the example in Figure 8. Flow Temperature is the warmer water temperature while Return Temperature is the temperature of the water returning to the water heater.

For other information such as Energy and Volume, the information about how this values are calculated is unclear. For example, the Volume displayed in the example shows a value of 376.038 m^3, but the water heater only has a capacity of 29 liters or 0.029 m^3. It is not possible to reset or configure those values in the software but user could maybe reset it in the energy meter itself.

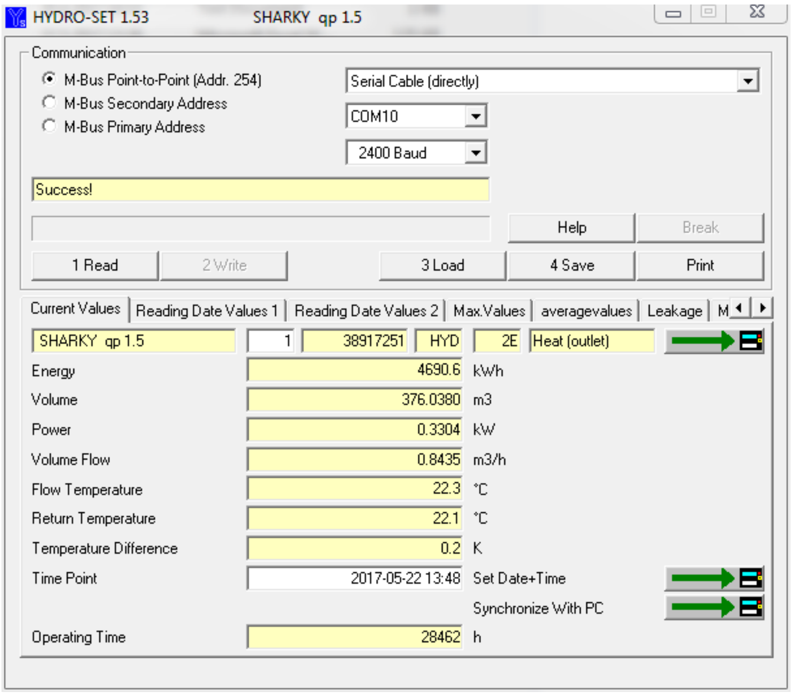

Figure 8. Hydro-Set software from Diehl Metering

3.1.4 Other components

Air cooling system is manufactured from AKG and made out of aluminum. It has a capacity of 2.9 liters and water entering this system will be cooled down by air convection and conduction of aluminum. As it is mainly used for cooling down coolant in the engines, there are no technical details regarding the heat loss of this air cooling system using water. Attached to this air cooling system is a fan and a motor that could be controlled by the control unit NXP from Vacon. The control unit has a RS232 interface and could be controlled externally. However, the fan and control unit are not included for the experiment part of this thesis. On a short notice, the motor gets heated easily and thus it could not be turned on for a long period of time, nor could it be turned on permanently as it will stop functioning for a while when it is overheated.

The water pump is used mainly in transporting warm water to the radiator. It can be turned on permanently and has an operating temperature from 2ºC to 110ºC, depending on the ambient temperature. There are several modes that it can operate in. The mode chosen for the experiment is PP1 which is the lowest proportional-pressure mode. There is only a button on the pump to switch between the modes. Additionally, the water pump is not controllable by any means and it has to be turned on to allow constant water circulation in the water heater system. When it is turned off, water will become stagnant in a position and the thermometers are not able to read the actual water temperature in the water heater.

3.2 Communication protocol M-Bus

The energy meter could communicate with external devices through three different interfaces. They are optical ZVEI, M-Bus or RS232. With the first interface, optical ZVEI uses light pulse or missing light pulses to send data in bit-format. This optical communication will have a higher priority compared to the other two interfaces. In M-Bus, communication is done over a two-wire line. RS232 interface contains a three-pole terminal strip which is marked with DAT, REQ and GND and uses a special HYD cable adapter to connect with a computer. Out of these three interfaces, RS232 is already installed in the energy meter and will be used as the communication interface between the energy meter and external computer. It is not to be confused that this RS232 interface also supports M-Bus communication protocol.

M-Bus stands for Meter Bus, it is developed by Professor Dr. Horst Ziegler from University of Paderborn in Germany in cooperation with Texas Instruments Deutschland GmbH and Techem GmbH as a way to fill the requirement for a method to link and read utility meters in a cost efficient way. This includes reading water meter to know the monthly consumption in a household. It consumes low power and could be powered by batteries or electric cable. It is a new European standard for remote meter reading and can be used for all types of consumption meters. Its communication system resents a common master-slave communication, where the master or central computer will send a request either to specific slave or all slaves for an answer. The slave here represents each metering device. M-Bus uses bus topology as this topology provides a reliable and cost-effective network to connect consumer utility meters. In terms of reliability, up to 250 slaves can be connected to a master using M-Bus protocol and these slaves can stretch over long distances. The bus topology provides a way to ensure high degree of transmission integrity and it is unusually insensitive towards external interference such as capacitive and inductive coupling. In the bus topology, the slaves are also electrically isolated to avoid ground loops from occurring. In terms of cost-effectiveness, M-Bus does not require shielding for the transmission medium and only a few components are required to make sure it operates. Besides, the slaves can be powered remotely from the bus.

The ISO-OSI reference model provides a standard communication platform to ensure different communication devices made by various manufacturers can exchange and interpret information in accordance with standardized procedures. The model divides communication functions into seven layers. In contrast, M-Bus has only four layers and the layer four, five and six in the ISO-OSI reference model is empty. Only the physical, data link, network and presentation layer are equipped with functions.

3.2.1 Installation of M-Bus Library

While M-Bus protocol was developed in the early 1990s, it has not been widely adopted compared to Modbus or other types of industrial communication protocols. This is perhaps due to the fact that M-Bus is developed for reading utility meters and there has not been a major breakthrough in the past decades regarding meter reading. However, the recent development in Smart Home and Smart Meter has seen the rise of M-Bus popularity. Smart Home is essentially the concept of new residential buildings where everything in the house is connected and can be controlled centrally and remotely. Smart Meter or Automatic Meter Reading (AMR) collects the power consumption of a building and transmits this information to utility for monitoring and billing purposes.

The energy meter in water heater system uses M-Bus protocol to communicate with external computer through a RS232 interface. Part of this thesis focuses on the investigation of communication protocol used in the energy meter. In order to facilitate automatic data exchange from water heater system to HEMS computer in the future, a software should be developed based on M-Bus protocol. There are currently two open-sourced libraries which can be used to extract information from the energy meter using M-Bus protocol. They are *libmbus*[13] and *jMBus*[14] developed from rSCADA and openMUC respectively.

Libmbus is a C-library that is used for encoding or decoding the M-Bus protocol. It can be installed using GNU autobuild tools in Windows operating system such as *MinSys* or installed with binary packages in Ubuntu system. It is discouraged to install *libmbus* on GNU platform on TUT computers as administrative right is needed to write files on the local hard disk drive. With Ubuntu, binary packages can be downloaded and installed easily in the command shell, the only trick is that Ubuntu is installed in TUT computer using Virtual Computer and user can only have internet access for Ubuntu by connecting it to a research network in TUT campus. The research network is located in microgrid laboratory. With libmbus, user can utilize the pre-written functions in C-language to send information to the M-Bus slave. The slave will answer in the command shell. The example below shows a request to the slave, asking for the physical address.

[13] More information from http://www.rscada.se/libmbus/
[14] More information from https://www.openmuc.org/m-bus/

```
sii$ mbus-serial-scan /dev/ttyS0
Found an M-Bus slave at physical address 2
sii$
```

Program 1. *Example of code in libmbus to ask for physical address of the slave*

Apart from the function mbus-serial-scan in the example above, there are many more functions in the library where user can use to extract information from the slave. The slave here is the energy meter while the master here is the host computer on which the library is installed. A suggestion in the future to automatically ask the information from the slave would be to create a while-loop that sends the function to read the water temperature every five minutes. It is not clear if user could save the information in the command shell in Ubuntu, given that the requested information from the slave will be displayed in the command shell.

jMbus is another library that works with wired or wireless M-Bus protocol. The website from www.openmuc.org/m-bus/ explains explicitly the details of installation. It is not installed on HEMS computer but the information from the OpenMUC's website is really useful in explaining the steps for installation.

4. OPTIMIZATION

The water heater system is installed as a controlled thermal load to be used in the microgrid in the future. It could dissipate heat and provide adequate heat demand to a household. Additionally, it could be centrally controlled by HEMS computer to turn on only when the requirements are met. These requirements are:

1. low electricity price; the price of electricity varies hourly in Finland. The market Elspot regulates the price for the upcoming day under this day-ahead pricing scheme by considering the bids from suppliers and demand estimate.
2. Sun's global irradiance; depending on which season of the year, global irradiance varies greatly. This would affect the amount of electricity that could be produced from PV panels
3. Outdoor temperature; So does the outdoor temperature which affects the heat demand of a house to maintain an adequate temperature.
4. Peak hour; The energy consumption in the house is higher during peak hour. In order to avoid bottleneck of electricity production, the water heater should avoid being heat up at times when the energy demand is high

4.1 Elspot electricity price

Electricity prices in Nordic and Baltic countries are determined hourly by trading power production and demand in a power market called Nord Pool. In the market, power suppliers such as the owners of wind turbines can decide the volume of electricity that they could produce and the price they want to sell for each hour. Buyers such as utility companies can set the volume they wish to purchase and the price they are willing to buy. The final price for each hour is formed by the balance between supply and demand. Majority of the prices are formed in the Elspot day-ahead market. A contract is made between the buyers and sellers for the delivery of power in the following day. The market closes at 12:00h Central European Time (CET) and the price will be set based on the balance of supply and demand. The trade is then agreed upon the involved parties. There is another market, called intraday market, that acts as a supplementary platform in case of changes happening between 12:00h CET and the next day. For example, there might be a power breakdown or system failure, the seller is not able to supply the agreed capacity. In this market, changes can still be made close to real time to bring the market back in balance.

In the early 1990s, Nordic countries decided to deregulate their power markets and combined their individual markets to form a single common market, where free competition takes over state-run power market. Baltic countries joined this power market in 2010 and now Nord Pool is the leading power market in Europe consisting of nine countries. The prices for each hour varies according to the intersection between supply and demand curve, as illustrated in Figure 9. Elspot day-ahead market defines peak hour (as seen in Pool, 2011) from 8:00h to 20:00h. There are two off-peak hours, the first one is from 0:00h to 8:00h and the second one from 20:00h to 0:00h.

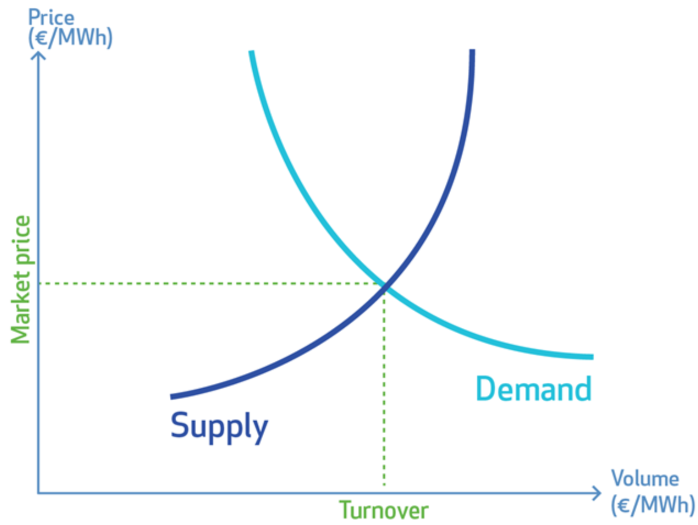

Figure 9. Supply and demand curve for Elspot day-ahead market[15]

Based on the classification of peak and non-peak hour, a heating strategy can be tailored for the central control. The water heater can be turned on in the hours when the price is the lowest in the day. Figure 10 below shows an example of classification of the price on the day.

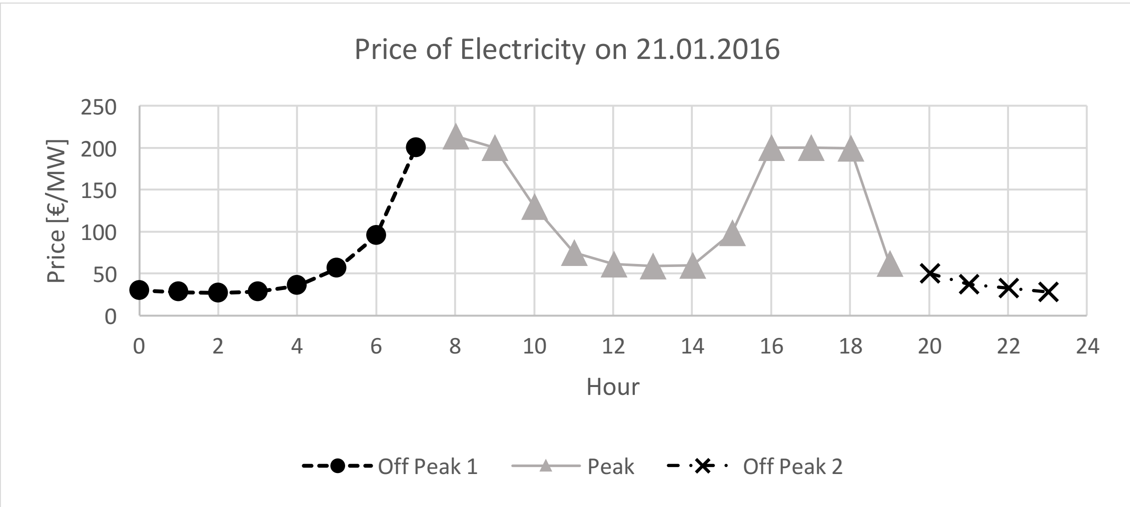

Figure 10. Price of electricity on according to Off-Peak 1, Peak and Off-Peak 2

The maximum price on that day is 214.25 €/MW from 7:00h to 8:00h while the minimum is 26.65 €/MW from 2:00h to 3:00h. While this day represents an unusual price difference

[15] Day-Ahead Market, https://www.nordpoolspot.com

and the average price for year 2016 is 32.27 €/MW, turning off the water heater system on 21.01.2016 from 5:00h to 8:00h could help to minimize electricity bill at that time.

The example above is a winter day in Finland and prices fluctuate a lot due to presumably cold weather and high demand in heating. The design of a central control in HEMS in the future should be able to make the decision on when to control the controllable load. A way to do this is to find out the average prices per volume for each Off-Peak 1, Peak and Off-Peak 2 categories of the next day through the acquisition from Elspot day-ahead data. If the hourly price is lower than the average price, electricity from the grid can be used for controllable loads in the house. The standard deviation could be used to facilitate in the decision making too. Table 3 shows the average price for each category and the maximum and minimum price of the day 21.01.2016.

Table 3. Average prices of electricity on 21.01.2016, €/MW

Min	Max	Average	Avg. Off-Peak 1	Avg. Peak	Avg. Off-Peak 2
26.65	214.25	91.92	129.99	62.30	36.91

The arithmetic mean and standard deviation for different hours in Off-Peak 1 tells a different story as the prices for the last two hours surges upward. Table 4 below shows that the standard deviation for all eight hours in Off-Peak 1 is five times higher than the standard deviation for the first six hours. This is due to the extreme increment in price in the last two hours. The smaller the standard deviation is, the closer each data is to the mean value. The control could make use of this analysis when the average and standard deviation for the hours in the next day is significantly higher than normal.

Table 4. Average and standard deviation for different hours in Off-Peak 1 on 21.01.2016

<table>
<tr><th>Hour</th><th>00-01</th><th>01-02</th><th>02-03</th><th>03-04</th><th>04-05</th><th>05-06</th><th>06-07</th><th>07-08</th></tr>
<tr><td>€/MW</td><td>29.65</td><td>27.82</td><td>26.65</td><td>28.05</td><td>35.26</td><td>56.01</td><td>95.03</td><td>199.96</td></tr>
<tr><td rowspan="3">Avg.</td><td colspan="6">33.91</td><td></td><td></td></tr>
<tr><td colspan="7">42.64</td><td></td></tr>
<tr><td colspan="8">62.30</td></tr>
<tr><td rowspan="3">S.D.</td><td colspan="6">10.27</td><td></td><td></td></tr>
<tr><td colspan="7">23.40</td><td></td></tr>
<tr><td colspan="8">56.45</td></tr>
</table>

Table 5 states the average price for each hour in 2016. Similar analysis can be made for each month instead of in a year since the weather variation for each month in Finland is stark and this will affect the production capability from renewable energy sources and heat demand. From the table, one can observe the trend that prices are lower in midnight and in the dawn. It becomes more expensive to buy the electricity in the day from 08:00h to 20:00h.

Table 5. Average hourly price in 2016, €/MW

Hour	**00-01**	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06-07**	**07-08**
Price	24.59	23.49	22.83	22.51	23.60	27.43	32.27	37.60
	08-09	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**
	40.41	39.94	37.78	37.46	36.92	36.32	35.11	34.53
	16-17	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
	36.13	37.99	38.16	35.27	30.60	29.71	28.08	25.72

4.2 Global irradiance and amount of energy PV produces

The sun emits energy through electromagnetic radiation by a process called fusion reaction. The sun's radiation flux per unit area or irradiance, measured in W/m^2, on earth is not a constant due to a number of factors. The cloud's formation blocks the direct irradiance falling on earth and the earth's self-rotation on an imaginary axis that is tilted at 23.5º as illustrated in Figure 11 affects the position of sun as seen on difference places around the world. For example in Figure 11, the sun seen in Hamburg is only 13º above the horizon during winter solstice, as the sun is perpendicular to the line south of the equator. Whereas in summer solstice, the sun is 60º above the horizon. The sun's position in the horizon has a tremendous effect on the global irradiance that falls on the place. The higher the global irradiance, the more electricity PV is able to produce.

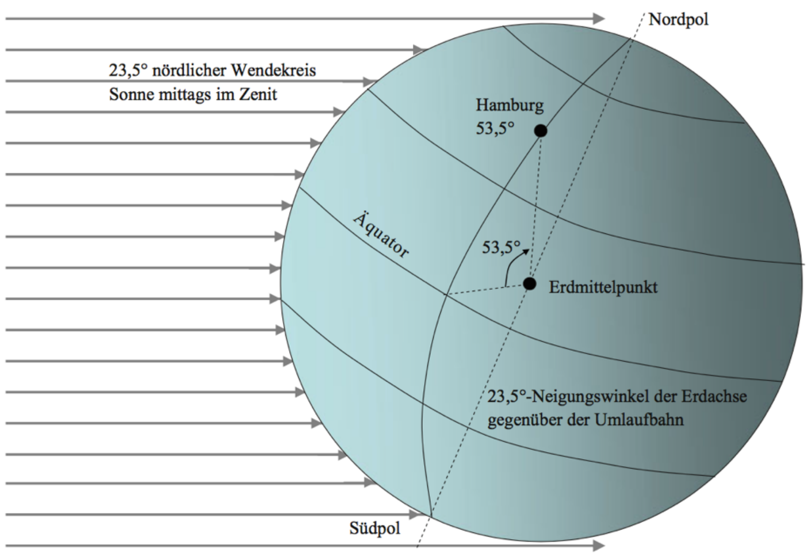

Figure 11. Earth's tilted rotational axis during winter solstice (Watter, 2015)

Global irradiance is the term for the addition of direct irradiance and diffused irradiance. Direct irradiance results from direct sunlight while diffused irradiance includes sunlight that is reflected or absorbed by the clouds and buildings. While the amount of global irradiance falling on a place depends greatly on the time of year, the average solar energy in Germany is 1000 kWh/m^2 (Watter, 2015).

Photovoltaics is a term referring to the conversion of sunlight into electrical energy by means of semiconductors. Non-conducting material like ceramic do not have freely-moving electrons and the outermost shell is filled with electrons. Only at very high temperature will a few electrons leave the shell and move freely. Thus, ceramic has a very low conductivity. On the other hand, conducting material like metals and alloys have freely-moving electrons or empty electron hole. Electrons can move freely at lower temperature and metals have higher conductivity. Semiconductor such as silicon are non-conducting element at low temperature by nature. They are elements which is located in the fourth group in the periodic table. Silicon has four valence electrons on the outermost shell and a stable configuration requires the shell to be filled with eight electrons. By heating silicon, the valence electrons will move freely and its conductivity increases with temperature. This characteristic can be further enhanced by doping effect. It is understood by introducing another element with either three or five valence electrons into silicon. In the case of doping silicon with phosphorus which has five valence electrons, the extra electron is weakly connected in the outermost shell as there are not enough electron hole. This increases the conductivity and the silicon becomes negatively-dope silicon or n-type silicon. A positively-doped silicon is doped with aluminum which contains an extra electron hole. A combination of a n-type silicon and a p-type silicon forms a diode, where current flows in one direction from anode to cathode, as illustrated in Figure 12. They are separated by a diffusion zone called PN-junction.

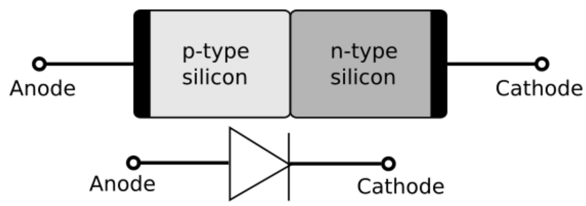

Figure 12. Diode consisting of p-typed and n-type silicon

The photons in electromagnetic wave through direct irradiance excite the electrons to move through the PN-junction in a diode, resulting in the photovoltaic effect. A PV cell has a diode and it can produce a pretty constant open-circuit voltage output from 0.5 V to 0.7 V. Open-circuit voltage is the potential difference across the diode when the current is 0 A. Meanwhile, a PV module consists of hundreds of PV cells that are connected either in series or in parallel or a combination of both to increase the power output. A PV panel mounted on the rooftop may consist of several PV modules.

The four terms that characterize a PV module are short-circuit current, open-circuit voltage, maximum power point and fill factor (FF). The efficiency of a PV module typically lies from 10% to 19%. Shadow caused by the cloud formation could lead to power loss on PV modules as the PV cell that is shadowed will not be able to produce any current.

The position of the sun in the horizon throughout the year as well as cloud formation will impact the amount of direct irradiance available. Factors such as wind speed and module temperature will affect the efficiency of the PV module to produce electricity.

A PV inverter will be installed in the microgrid laboratory in the future, where it converts direct current (DC) from a DC-generator to alternating current (AC) and supply it to the microgrid. Power production from PV depends greatly on the direct irradiance from the sun. However, direct irradiance is influenced by the shadow from the cloud and the by the weather. Rainy and cloudy days will affect the power production greatly. Another factor that affects power production is the position of the sun in the horizon or the time of the year. These factors are unpredictable and accurate estimation is required to predict the amount of direct irradiance available. A suggested way to deal with the uncertainty in the estimation of direct irradiance in a dense population area is stated in (Shinozaki et al., 2016) where correlation between cloud movement and solar irradiance is investigated. A statistical method called Gaussian process regression or kriging for all information collected from 25 distributed observation points is used to improve the estimation of solar irradiance.

4.3 Outdoor temperature and heat demand in a house

Heating constitutes a large amount of energy consumption within a house. This section talks about the factors that contributes to heat loss in a house. Heat demand in a house refers to the amount of heat energy required to keep a house warm throughout the day, it is dependent on the outdoor temperature and the time of the year, as well as how well a house is insulated. While older buildings do not have the best insulation, new buildings are usually built to minimize the cost of heating by having good insulation and as a result, the house is more energy efficient and the cost of heating can be lowered.

Knowing the heat demand in the house could aid in the choosing the suitable Heating, Ventilating and Air Conditioning (HVAC) for the house. In Finland, as cold weather dominates most time of the year, heating in the residential buildings come from district heating, air or ground heat pumps, electrical heater or burning of wood. Water is normally warmed and used as the medium to transport heat around the building. Warm water enters the house through hoses and goes to the radiator where most heat is dissipated. Cold water leaves the radiator and goes back to the heating chamber where heat exchange takes place. In the case of district heating, the by-product of power generation in the form of heat energy is used to heat up the water. Steam of hot water is supplied to nearby residential or commercial buildings for heating purpose. In the case of water heater system, water is heated from electricity and the heat is dissipated in the air cooling system. The following paragraph gives a general idea about the calculation of heat loss and heat demand in a house.

Heat loss calculation of a building is normally performed to estimate the heat demand that a building needs. Usually the calculation takes the coldest night of the year into consideration, as the lowest temperature usually occurs during the night. The calculation usually does not include the energy gained by a house through solar radiation. There are several ways that a house can lose its heat to the surrounding. The main factors are:

- Heat loss through walls, floors, windows, ceiling and doors
- Heat loss through the leakage and cracks for example at the side of windows and doors.

There are three ways in which heat is transferred, they are conduction, convection and radiation.

Conduction is defined as the transfer of heat through a medium by direct contact. On a microscopic scale, conduction is the transfer of heat energy through the vibration of each molecule. Molecule in a solid with higher temperature will vibrate faster and this affects the neighboring molecules. This interaction causes neighboring molecules to vibrate faster and as a result, the substance becomes warmer. Thermal conductivity λ describes the ease in which heat is transferred while thermal resistance R is a measure of a substance's resistivity against heat transfer. A medium can either be heat conductor or heat insulator. The medium is said to be heat conductor when it has low thermal resistance or high thermal conductivity. Such medium can be steel or aluminum, which is the material used in air cooling system in microgrid laboratory. Meanwhile, heat insulation is the opposite of heat conductivity; it describes the process of retarding the heat transfer in a medium. Such medium has high thermal resistance or low thermal conductivity. Typical heat insulators used in the buildings are polystyrene foam, glass wool or fiberglass. Thermal resistance is commonly used in the calculation of heat loss of a building, as materials with higher thermal resistance are better off to minimize heat loss to the surrounding. Mathematically, thermal resistance can be described as:

$$R = \frac{l}{\lambda * A} \tag{1}$$

Where R is the thermal resistance, l is the thickness of insulation, λ is the thermal conductivity of the insulation material in unit W/m*K and A is the surface area of the heat flow section. The unit for thermal resistance is K/W. The value for thermal conductivity λ is a constant and each material has its own thermal conductivity. Thermal resistance varies with the thickness of insulation. Inside the water heater, there are three layers of materials consisting of inner wall, insulation and outer wall. Each material has its own value for thermal conductivity and heat loss occurs through thermal conduction.

Heat loss by conduction is shown in the following equation:

$$Q = U * \Delta T \quad (2)$$

Where Q is the heat loss by conduction, U is the thermal conductance or reciprocal of thermal resistance R and ΔT is the difference in temperature on the surface of each layer. For example, to calculate the heat loss of the water heater, total thermal resistance can be calculated by connecting each layer in series, similar to calculating the overall electrical resistance in a circuit as seen in the equation (3).

$$R_{total} = R_{inner\ Wall} + R_{insulation} + R_{outer\ Wall} \quad (3)$$

The thermal resistances of the material used in the water heater are not known and thus it is not possible to calculate the total thermal resistance of the water heater. Meanwhile, heat loss through the air cooling system can be calculated by measuring the water temperature of T_{outlet} and T_{inlet} and substituting it into equation (4).

$$P_{loss} = \varrho_{water} * \dot{V} * c_w * (T_{inlet} - T_{outlet}) \quad (4)$$

The volumetric flow rate of water is a measured quantity from energy meter. As T_{inlet} is smaller in value than T_{outlet}, the negative sign from the temperature difference in (4) indicates the loss of power from the water heater system.

Heat transfer by convection occurs normally through fluids or air on the surface of water hose. Electrical energy is converted to heat energy by the resistor in water heater and it is through convection that this heat is transferred through the water within the water heater. Warmer water becomes less dense and flows upwards to the surface while colder water moves downwards. This forms a natural water circulation inside water heater and mixes the warm and cold water. In the air cooling system, large surface area eases the heat transfer through convection to the surrounding.

Heat is transfer by the photons of electromagnetic wave in a process called radiation. It happens usually only on very hot surfaces and does not concern the heat transfer in the microgrid laboratory.

The heat demand of a house can be determined by calculating the heat loss of a house. Heat is lost through conduction in the walls, windows, doors and floor as well as the leakage or cracks in the window frames or doors. Knowing the heat demand of the house especially in the cold seasons can help to choose the size of heating system in a house. A house or room can maintain a desired temperature if there is a net gain of heat supplied to the house. Net gain occurs when the heat supplied is more than the heat demand. The water heater system has a 1.8 kW water heater with a volume of 29 liters. A single house of 140 m^2 in Helsinki according to (Zangheri, 2014) requires 4200 kWh of heating in January (based on 30 kWh/m^2) as depicted in Figure 13. Scaling down the size of house to a 30 m^2, the heating demand in January is 900 kWh. This would require the water heater system to operate 16.7 hours per day in January to provide that amount of heating energy following the equation (5).

$$Q_{heating} = P_{rated} * t_{hour} \tag{5}$$

The heating demand in a single house for every month differs according to the weather. Heating demand in Helsinki is highest in winter from November to March and lowest in summer from June to August.

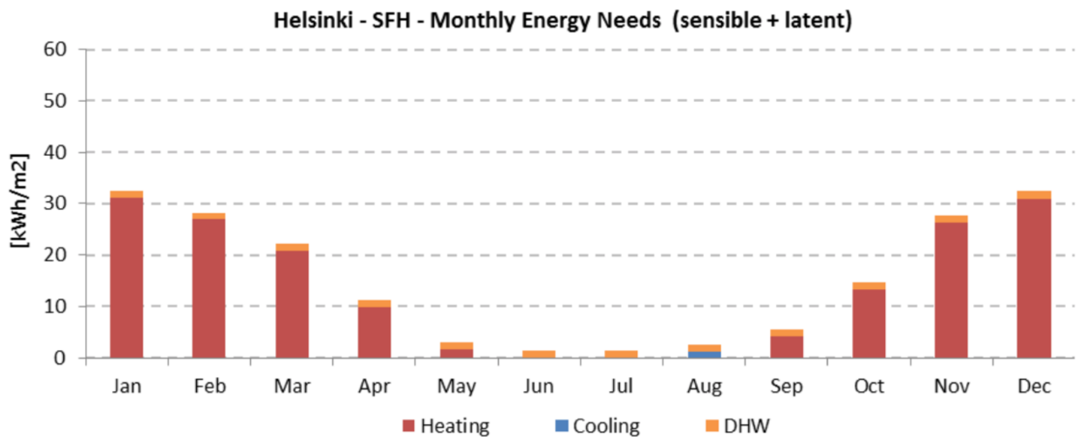

Figure 13. Monthly energy demand for heating, cooling and domestic hot water in single house in Helsinki

4.4 Time of usage and peak hour

It would be inevitable to heat the water heater in the winter when power production from PV is not available but space heating in the house is in high demand. Electricity price is charged according to amount of kWh that is consumed. If the water heater, which has a rated power of 1.8 kW, is turned on for a full one hour, the amount of energy consumption is 1.8 kWh. Likewise, turning the heater on for half an hour consumes only half of the energy which is 0.9 kWh. And turning on the water heater for half an hour in two-hour period consumes the same amount of energy compared to turning it for one full hour. The energy consumption depends on the period of time in which an electrical appliance is switched on. During the peak hour, load switching is useful to reduce the load demand. A high load demand during the peak hour does not only mean higher electricity bill, but it will cause supply constraint from utility's point-of-view and may lead to higher power import from neighboring countries. Hence, Demand Response (DR) is introduced as a mechanism to switch the load from peak hour to non-peak hour so that the congestion in power supply can be prevented.

5. EXPERIMENT

The idea of how the water heater system in the microgrid laboratory would work in the future is that once the communication between the energy meter and HEMS computer is done, the energy meter can send information such as water temperatures to the computer via a gateway in real time. The computer would act as a central control that manages the heating sequence of the water heater system, by considering other factors such as the electricity price, availability of solar energy and heat demand in the house. These factors are discussed in the previous chapter.

This chapter describes the experiment or measurement that has been conducted on the water heater system to find out about the rate of heating and rate of cooling of the water heater. The goal is to find out if the heating and cooling are repetitive and to know the amount of time required to heat or cool the water. The relationship between time and water temperature will be approximated using best line fitting and the approximated solution will be presented in the form of equations. Moreover, the equations will be verified by comparing the calculated and the measured values for water temperature. In the final part, the equations will be integrated to the production following program from (Esner, 2014) that currently runs in HEMS computer. The possibility of the integration into HEMS will be documented in this chapter as well.

5.1 Planning of the experiment

The aim of this experiment is to find if there is a relation between time and temperature for heating and cooling of the water. With the Hydro-Set software, one can read the values of water temperature from the thermometers installed in the water heater system. Naturally, one can calculate the water temperature based on the thermodynamic equation (6) as stated below.

$$Q = m * c_w * \Delta T \tag{6}$$

Where Q is the energy in J supplied to a system, m is the mass of water in kg, c_w is the specific heat capacity of water in J/kg K and ΔT is the change of water temperature in K. The amount of energy here could be known by multiplying rated power P_{rated} of the water heater, which is 1.8 kW, with time t the water heater is turned on in s, as seen in equation (7).

$$Q = P_{rated} * t \tag{7}$$

By substituting equation (6) and (7) one can calculate the water temperature based on the electrical energy injected to the system. However, this equation works well in an adiabatic system, where there is no heat transfer between the thermodynamic system and the surrounding. In the water heater system, there is heat loss to the surrounding through air convection and thermal conduction during heating and cooling. Besides, the exact amount of water in the water heater system including the water flowing in the hose and water pump is not known. Modelling an exact thermal system in this case to understand the thermodynamic behavior of this water heater system is not the main purpose of this thesis, but rather to understand more about the possibility of having a controlled thermal storage in the microgrid and to use suitable measurement technique to conduct the measurement of water heater. The measurement would provide a mean to determine relationship between heating time and water temperature experimentally. It is hoped that through this experiment, the water temperature related to heating and cooling time can be approximated and integrated into HEMS, before the actual communication link between water heater system and HEMS computer is established.

Heat will always travel from higher temperature to lower temperature in order to achieve thermal equilibrium. This causes the heat to be transferred away from any warmer object and it is known as heat loss. The amount of heat loss to the surrounding is caused by several factors in the water heater system, they are:

1. Heat loss in the water heater: the heater is insulated but some heat energy will still loss due to thermal conduction of the inner wall, insulation layer and out wall of the heater.
2. Heat loss in rubber hose: rubber hose is used to transport the water from water heater to the air cooling system.
3. Heat loss in cast iron connectors and valves: there are numerous connectors and valves mounted in the water heater system to connect each component in the water heater system with rubber hose.
4. Heat loss in air cooling system: Air cooling system dissipates heat to the surrounding using natural cooling. The higher the water temperature, the faster the heat dissipation becomes.
5. Heat loss in thermometer: Part of the heat will be transferred to the thermometer. As temperature cannot be measured directly, it relies on the reproduction of another extensive variable such as electrical resistance of platinum to be measured. This is called indirect measurement. The heat loss in this case is minimal but it exists.
6. Heat loss in water pump: Heat will be transferred to the components inside the water pump such as the housing and turbine when warm water goes through it.

Equation (8) below shows that the electrical energy applied to the water heater is an addition of heat energy gained to raise the temperature of water and heat energy that is lost to the surrounding. The electrical energy is the product of rated power of water heater and time. Heat loss in the whole water system can come from various sources as listed in the bullet points above.

$$Q_{electrical} = Q_{gained} + Q_{loss} \tag{8}$$

For every heat energy gained in the water heater to raise the water temperature by 1ºC, some energy is lost to the surrounding. Thus, it takes a longer time to actually heat the water than theoretical calculation without considering heat loss.

The measurement is divided into two parts; heating and cooling. The heating starts as soon as the water heater system switches on and the starting time is recorded. Reading will be taken using Hydro-Set software at the interval of ten minutes. The software takes approximately twenty seconds to get the reading. As the time in Hydro-Set is displayed up to minute-precision, the exact second when the reading is taken remains unclear. It takes a while for the master to send a request to a slave and for the slave to reply to the master. The software is the master in this case while energy meter is the slave. Hence, in the experiment, assuming that the master takes half of the total time to send request and the slave also takes half of the total time to send a respond back to master, it takes ten seconds after reading is requested to get the actual value of water temperature. The total time needed for the water temperature to rise from room temperature to its maximum temperature at around 56ºC will be recorded and the heating is stopped.

For the cooling part, temperature is recorded at an interval of ten minutes before the temperature drops below 50ºC and then the measurement interval changes to thirty minutes due to rapid changes at higher temperature gradient. A total of three sets of measurement is carried out for heating and cooling respectively.

5.2 Limitation and assumption

The thermometers Pt500 is a form of resistance thermometer and it has been installed in the water heater system beforehand. For this reason, the calibration of the thermometer is not possible. The thermometer has a sensitivity of 0.125K but the display value is only up to one decimal place, meaning there is a loss in rounding off the actual values. The water pump has to be turned on constantly to enable the reading of the water temperature, which in the case for cooling, it is not deemed to be accurate as there will be heat loss in the hose and air cooling system. Additionally, there is no information regarding the tolerance of Pt500. Normally, there are two classes for tolerance for the more commonly used Pt100; class A and B. For each class, the change in resistance of the metal in response to the temperature varies according to the temperature it measures. The information about the resistance thermometer Pt500 used in the water heater system is not available.

The microgrid laboratory is located in a big hall and the air inside is regulated by the university. It is assumed that the room temperature or air temperature inside the hall remains constant throughout the day. The hall is a lot bigger than the size of the water heater and there is air flowing constantly from air ventilation. Hence, the heat produced by the water heater is not enough to have any effect to raising the room temperature.

Measurement of water temperature inside the water heater is not possible as there is no thermometer inside the tank. The first thermometer which measures hot water coming out from the tank locates right before the entrance to air cooling system. The water temperature at this point is assumed to represent the water temperature inside the water heater. There are several assumptions that are also made for simplification reason in the experiment. The water is assumed to have uniform temperature distribution inside the water heater and the temperature T_{outlet} of the warmer hose is assumed to represent the water temperature inside the tank.

5.3 Results and Analysis

5.3.1 Heating

The heating of the water heater system took about 70 minutes to reach the maximum temperature. Figure 14 shows the graph of temperature of T_{outlet}against time in the first set of measurement. Temperature is measured at an interval of ten minutes until the maximum temperature is reached. It is best to avoid activating the overheating protection in which the mechanical thermostat turns the heating off. The reason is that once the thermostat turns off the heating, the water heater can no longer be turned on until the bimetallic strip in thermostat returns to original position. This will take some time before heating can be resumed.

The relationship between these two variables in heating can be approximated using line of best fit, where a straight line is drawn on the graph to describe the dependency of each variable as close as possible. This is illustrated in Figure 15.

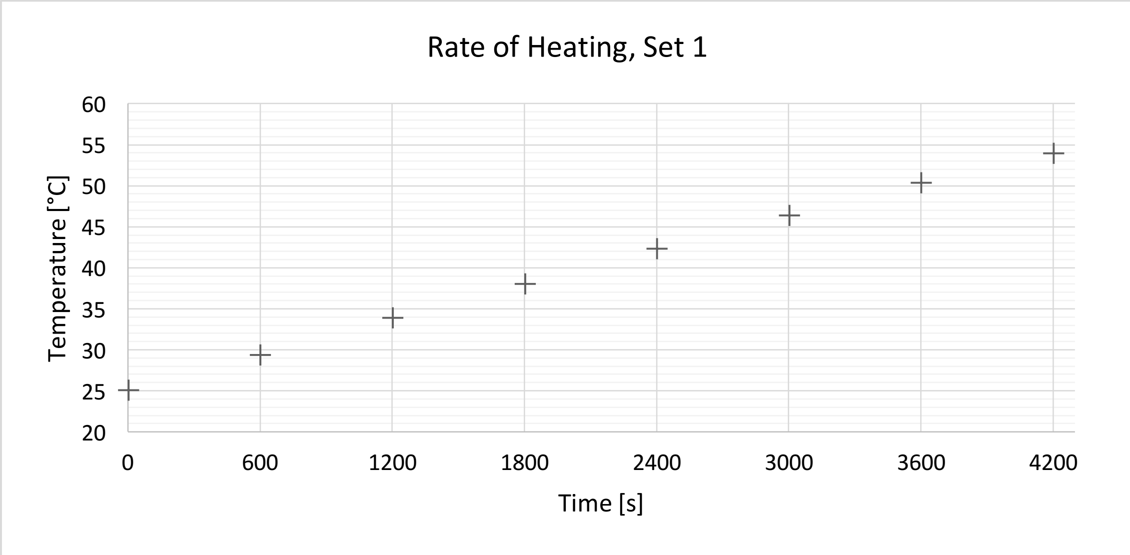

Figure 14. Temperature against time graph for heating

The straight line displayed here is drawn as a trend line in Excel, which is calculated based on the method of least squares fit. If the line represents a linear relation, its equation is expected to be in the general form of a linear equation (9).

$$y = A * x + B \tag{9}$$

Where y is the dependent variable, A is the slope of the line, x is the independent variable and B is the y-intercept of the line. Least squares fit method is a mathematical procedure for finding the best fit curve for a given set of points by minimizing the sum of squares of the offsets (or residual) of the points from the curve. The curve could follow any shape from linear to exponential to quadratic, depending on the nature of relation of the set of points. Squaring the deviation would prevent having a horizontal slope as the positive and negative deviation would sum up each other. While Excel can display the line of best fit equation on the graph, the values calculated from Excel usually are rounded off for simplicity reason and one cannot calculate the uncertainty of the calculated dependent variable.

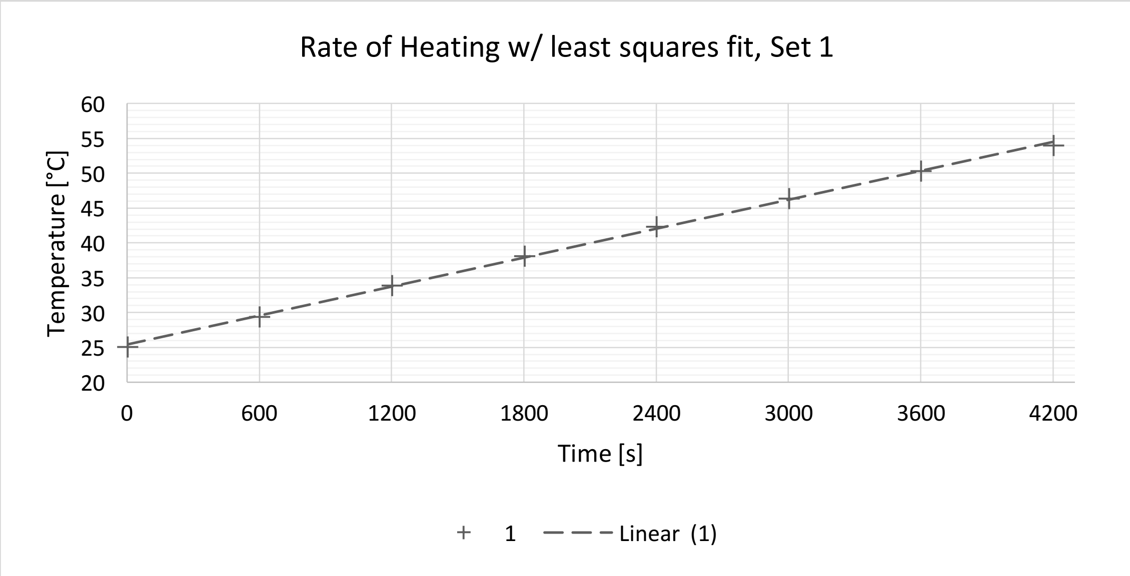

Figure 15. Best fine line to approximate the linear relation between the variables

In (Kurur, 2012), the formulas for using least squares fit method to calculate the slope b_1 and y-intercept b_0 is explained in detailed and it is shown in equation (10) and (11) below.

$$b_1 = \frac{\sum_{i=1}^{n}(t_i - \bar{t}) * (T_i - \bar{T})}{\sum_{i=1}^{n}(t_i - \bar{t})^2} \tag{10}$$

$$b_0 = \bar{T} - b_1 * \bar{t} \tag{11}$$

Where $\bar{T}$ is the average value of all measured temperature while $\bar{t}$ is the average value of n data points as seen in equation () and (13) below.

$$\bar{t} = \frac{\sum_{i=1}^{n} t_i}{n} \tag{12}$$

$$\bar{T} = \frac{\sum_{i=1}^{n} T_i}{n} \tag{13}$$

Least squares fit method works when there is a minimum of five data points available and the more the data points, the better it is to approximate the relation for the given set of data. The values for the slope and y-intercept in three sets of measurement by substituting the average temperature and time into equation (10) and (11) are shown in Table 6.

Table 6. Values of slope and y-intercept for all three sets of experiment

Set	Slope b_1	Y-intercept b_0	R^2-Value
1	0.006926587	25.4166673	0.99912
2	0.007015335	27.5808716	0.99961
3	0.007049603	26.2833337	0.99977

R^2-value is a mean to measure the accuracy of the approximated solution. It is also known as correlation coefficient. Its value ranges from 0 to 1 and the higher the value is, the more accurate that approximated solution represents the relation of the given data points.

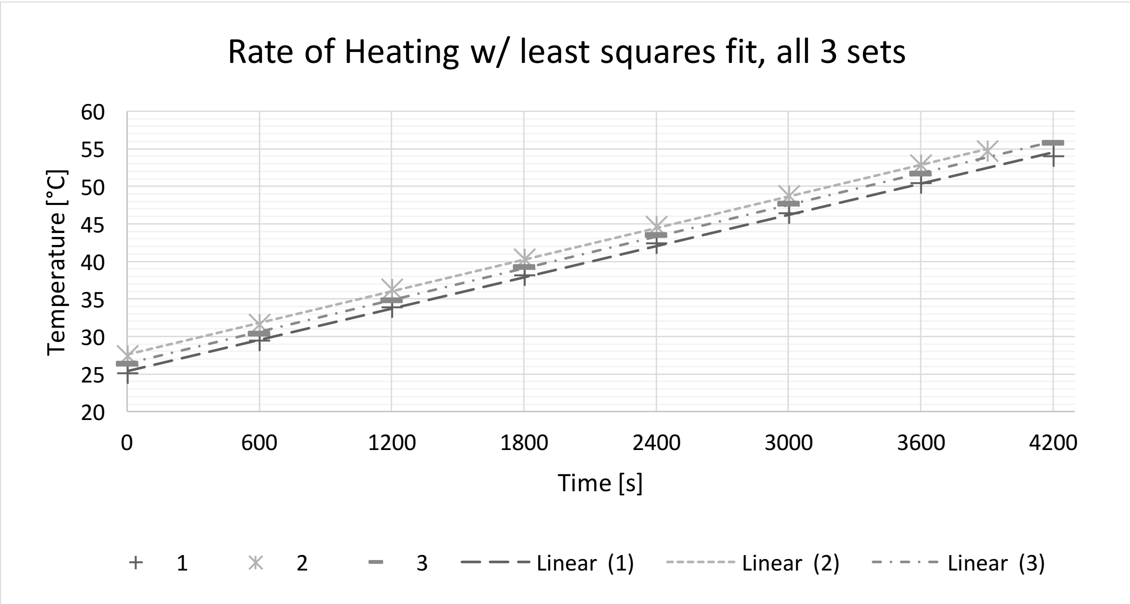

Figure 16. Results for all measurement for heating

The arithmetic mean for the three slopes are taken as the final value for the slope in the approximated solution. Y-intercept b_0 represents the starting temperature for heating and its average value will not be taken into account as it increases linearly in the approximated solution. The standard deviation is less than 1%, showing that the slopes from all three sets of measurement are quite similar and the heating process is repetitive. The result is predictable as the water heater system is not a dynamic system where no additional mass flow of fresh water is added to the system. The only factor that would affect the heating time is the addition of impurities in the water such as rust and other sediments formed as a result of oxidation in the water heater system.

Table 7. Arithmetic mean and standard deviation of slope b1 from all measurement

	Slope b_1
Arithmetic mean, $\overline{b_1}$	0.006997175
Standard deviation, σ_{b1}	0.000051837

This arithmetic mean value will be taken as the final value for slope b_1 and the approximated solution to describe heating can be shown in equation (14) below. The room temperature of 20.8ºC is used as the y-intercept in this case, as thermal equilibrium in the laboratory hall is reached at this temperature.

$$T_{outlet} = 0.00697175t + 20.8 \tag{14}$$

Similar approach to calculate the approximated solution for T_{outlet} has been used to calculate the approximated solution for T_{inlet}. The solution is presented in equation (15) below. This general form of approximated solution for inlet temperature has a y-intercept of 20.8ºC, which is the room temperature and also the point where thermal equilibrium between water heater system and laboratory hall is reached.

$$T_{inlet} = 0.00692803t + 20.8 \tag{15}$$

5.3.2 Cooling

The cooling process begins as soon as the water heater is turned off. The cooling time starts thereafter. The water temperature of T_{outlet} is measured at an interval of 10 minutes in the first hour and then at an interval of 30 minutes. During cooling, water pump is still turned on so that the thermometer could measure the water temperature. It takes approximately 7 hours for the temperature to drop 20ºC. The cooling process is repeated three times and the average values for each approximated solution are used in the finalized solution, the same procedure compared to heating process. The result of the first set of cooling measurement is illustrated in Figure 17 below. Cooling occurs as a net result of heat loss to the surrounding. This includes heat loss in the rubber hose, connector, air cooling system, water pump and lastly thermometer, as temperature is measured indirectly through another physical quantity such as resistance. At the first glance, the cooling process resembles a negative exponential behavior. Negative exponential behavior is characterized by rapid decrease initially. The rate of decrease reduces gradually over time. In this case, temperature drops are rapid at the beginning due to the higher temperature difference with room temperature. The process begins to slow as the difference decreases over time as thermal equilibrium of both the laboratory hall and water heater system is achieved.

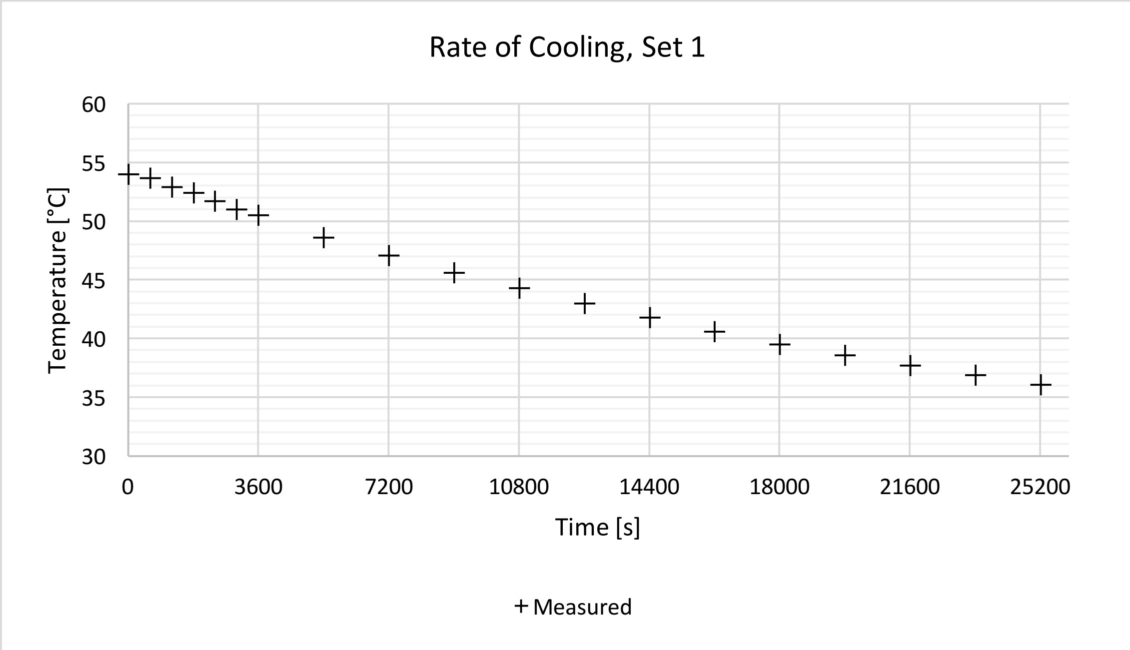

Figure 17. Temperature against time for cooling, Set 1

Applying the exponential trend line in Excel to the data point yields the exponential line as shown in Figure 18 below. Excel provides an equation for the trend line or best fitting curve to describe the relation of the data points. Theoretically, the temperature, calculated using the equation displayed on the graph, will fall exactly on the best fitting curve. However, the equation's coefficients have been rounded off and substituting the time as x-variable into the equation will result in increasing error as seen in diamond-shaped point in Figure 18.

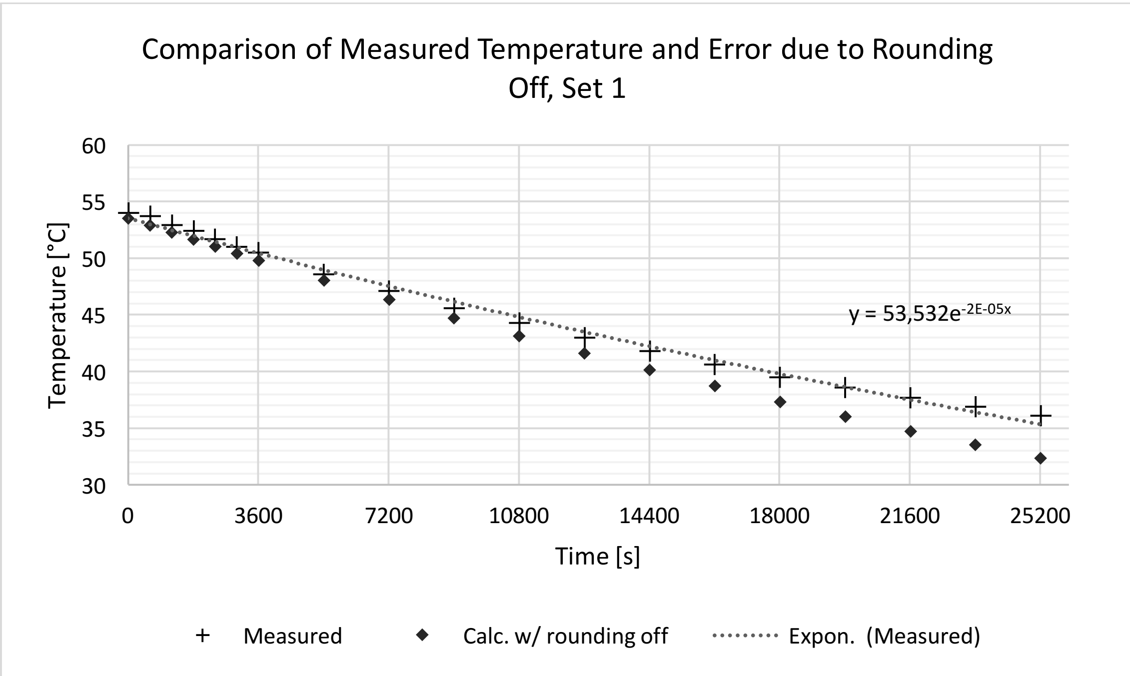

Figure 18. Comparison of calculated and measured temperature for cooling

This error is caused by rounded values of the coefficient. As x-variable increases, the error will also increase. As a result, the calculated temperature with rounded off coefficients deviates more from the best fitting curve.

Calculating the coefficients using the formulas for least squares fitting method can solve this problem. The general form of a negative exponential equation is seen in (16).

$$y = A * e^{-B*x} \tag{16}$$

Where y is the dependent variable, A is the y-intercept, B is the coefficient and x is the independent variable. Both A and B can be calculated mathematically but they can also be defined using Excel function *Linest*. Table 8 shows the calculated values of A and B for all three sets of measurement using the Excel function *Linest.* Linest uses least squares fitting method to calculate the coefficients for line of best fit. Combined with other functions in Excel, it can also be used to calculate the coefficients for other curve of best fit such as exponential, logarithmic, polynomial and power. The y-intercept A represents the starting temperature for cooling.

Table 8. Values of y-intercept A and coefficient B for all three sets of measurement

	y-intercept *A*	**Coefficient *B***
1	53.5320479	0.000016453
2	54.1098747	0.000016970
3	55.1738738	0.000017328

Figure below shows the calculated temperature based on the parameters from Table 8. The calculated temperature now falls on the exponential curve. The error due to rounding off has been removed. The arithmetic mean and standard deviation for coefficient B are tabled in Table 9 below. The standard deviation is less than 1% of the arithmetic value.

Table 9. Arithmetic mean and standard deviation of coefficient B from all measurement

	Slope b_1
Arithmetic mean, $\bar{B}$	0.0000169167
Standard deviation, σ_B	0.0000003592

The final approximated solution for cooling is shown in equation (17) below.

$$T_{outlet} = 56e^{-0.0000169167*t} \tag{17}$$

The starting temperature 56ºC is used because this is the maximum temperature the water heater can operate without activating the overheating protection. For any further calculation using this approximated solution, this temperature can be replaced by any starting temperature.

Similar approach to calculating the approximated solution for T_{outlet} is used for T_{inlet}. The approximated solution for T_{inlet} is shown in equation (18).

$$T_{inlet} = 56e^{-0.0000167135*t} \quad (18)$$

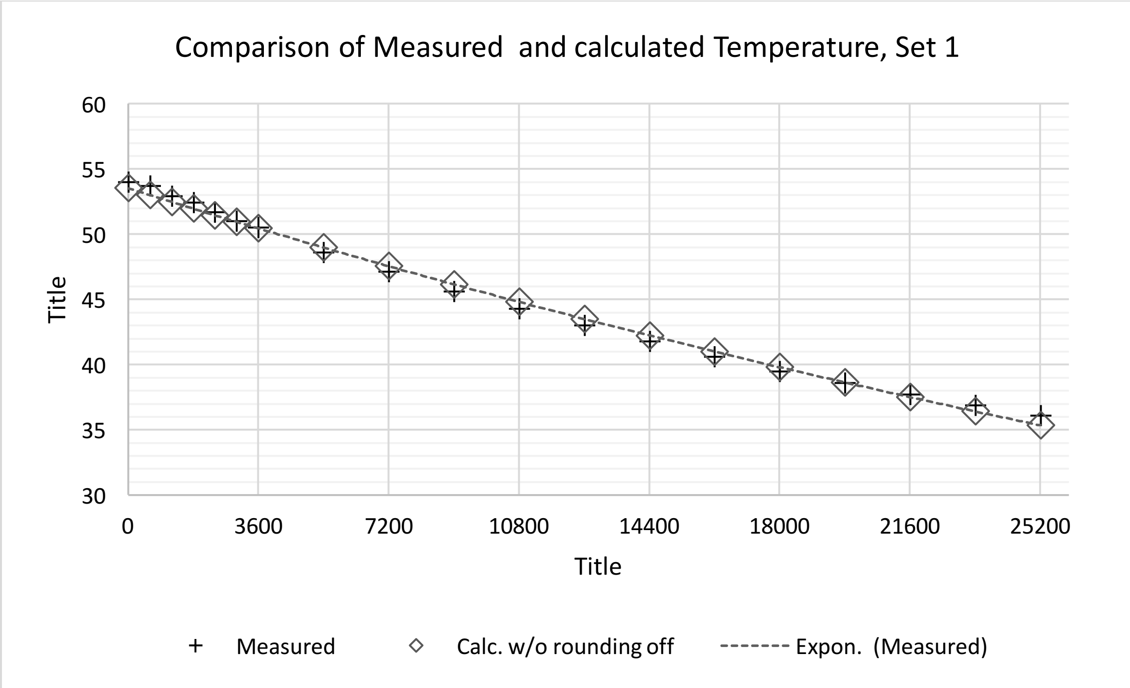

Figure 19. Comparison of Measured and Calculated Temperature, Set 1

5.4 Verification

The verification process aims to verify the accuracy of the approximated solutions for heating and cooling by comparing the measured and calculated temperature in different heating and cooling scenarios. There are four heating and cooling scenarios which can be grouped by the time. In the first scenario, water heater is turned on for 10 minutes and then turned off for another 10 minutes. This sequence repeats for two hours or when the maximum temperature is reached. The heating pattern repeats for heating and cooling time of 15 minutes, 20 minutes and 30 minutes. This alternating heating and cooling sequence aims to replicate real life heating scenario when there is a window of for example, two hours for abundance of sun light or cheaper electricity price. The water heater takes 70 minutes to reach the maximum temperature. There might not be enough resources to continuously heat the water for 70 minutes. Thus, through this verification process, it can be investigated if the approximated solutions can be used for calculating alternating heating sequence.

Each figure for different heating and cooling time shows the measured temperature in T_{outlet}, calculated temperature using the heating and cooling equations and the difference between each temperature. Here the difference is calculated as seen in equation (19) below. A positive temperature difference signifies a greater measured temperature.

$$T_{Difference} = T_{measured} - T_{calculated} \tag{19}$$

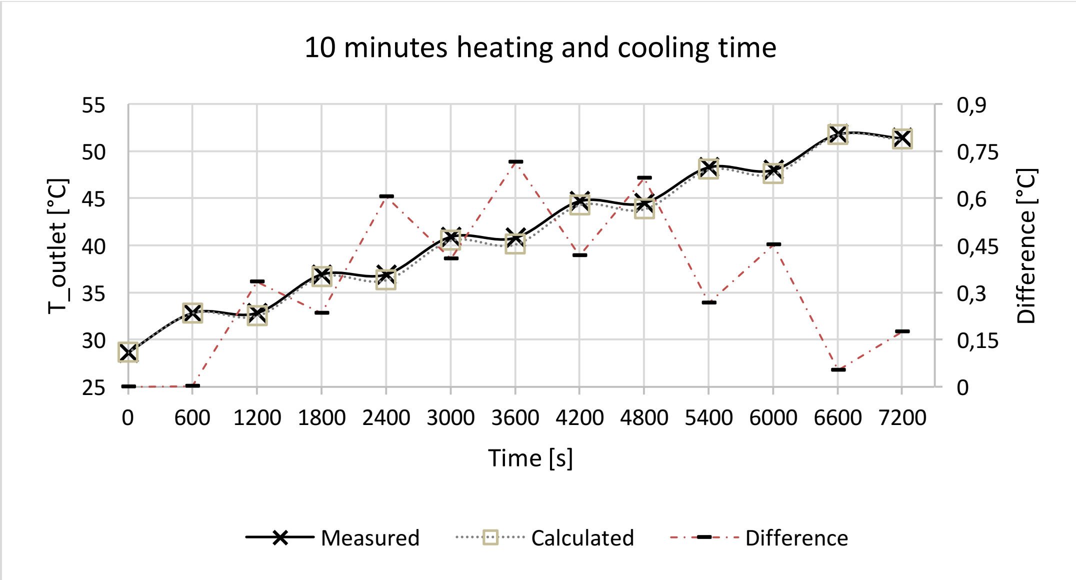

Figure 20. 10 minutes' heating time

The temperature difference for 10 minutes heating and cooling time has a maximum value of 0.75ºC. It can be seen that the curve for temperature difference has a positive gradient upon each cooling process. The process is stopped after two hours as a further heating will lead to exceeding the maximum temperature.

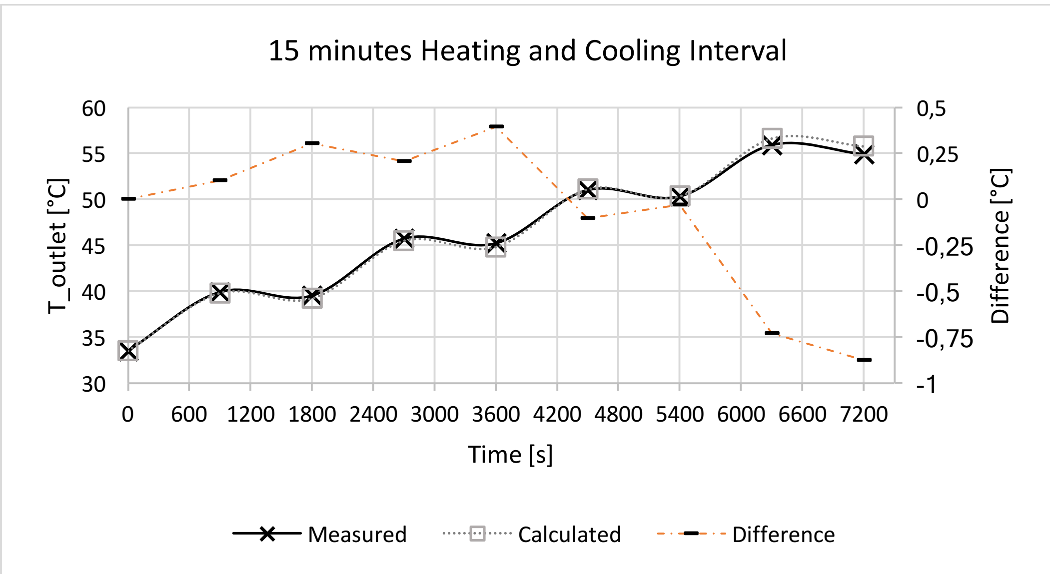

Figure 21. 15 minutes' interval

Figure 21 illustrates the result for 15 minutes of heating and cooling interval. The verification process is continued in the afternoon after rapid cooling by turning on the fan. As a result, the starting temperature is higher than usual. The temperature difference stays in the positive area in the first half of the process but becomes negative towards the end of the process. It shows that the calculated temperature eventually becomes greater than the measured temperature.

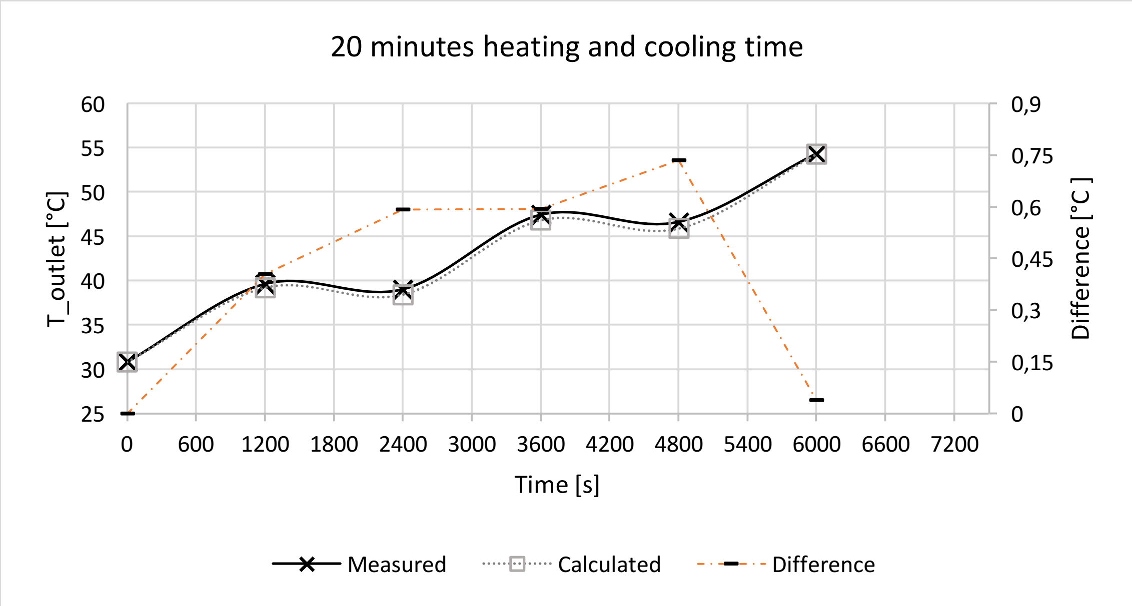

Figure 22. 20 minutes' interval

The heating and cooling sequence of 20 minutes sees similar temperature difference behavior compared to 10 minutes' interval. The temperature difference increases during the cooling process.

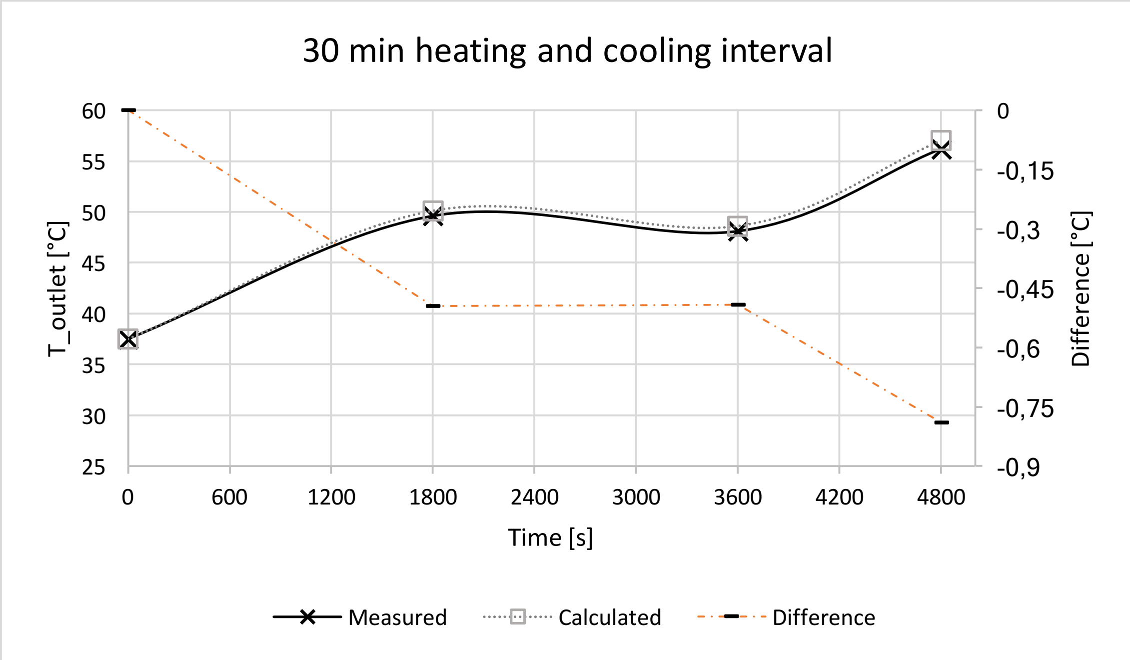

Figure 23. 30 minutes' interval

The result of 30 minutes heating interval shows that the calculated temperature ends up higher than the measured temperature. In fact, it is observed that the calculated temperature in all four heating intervals is always higher than the measured temperature. This phenomenon can be explained by the nature of thermal equilibrium and thermal inertia. Considering the following scenario, when water inside the water heater has not been heated in a while, its temperature is equivalent to the room temperature, it can be said that the water heater is in thermal equilibrium with the laboratory hall. All other components in the water heater system also reaches the thermal equilibrium with the laboratory hall. Thus, it will take a longer time to heat up the system. It will take less time to heat up the system had the other components been warmed previously. During the verification process, water is heated previously and the water heater system is not in thermal equilibrium with the laboratory hall. The other components such as air cooling system and water hose are already warm. This leads to measured temperature being always higher than the calculated temperature in the beginning, as the temperature difference is always positive in value in the first half of the process.

The second observation regarding the thermal inertia is that, when there is a pause in between heating, thermal inertia will be lost. In physics, inertia is explained as the resistance of any physical object to the change of its state of motion. When the heating of water is stopped, the water particles will still vibrate for a little while and collide with other particles. As a result, the temperature will still continue to rise for a little bit. The same goes to cooling process. This repeated resistance to the change of motion during different heating and cooling intervals results in calculated temperature being higher than measured temperature in the second half of the process. As a result of these two phenomena, temperature difference will be positive but gradually decrease towards the end of the verification process.

In conclusion, the equation for heating and cooling can be used to calculate the water temperature based on the time. But there is difference between the calculated and measured temperature value and this difference is about 0.8ºC in magnitude.

5.5 Calculation of heat output

The heat dissipated by the air cooling system can be calculated based on the difference of temperature $T_{inlet} - T_{outlet}$ and the volumetric flow rate of water as shown in equation (4), where dissipated heat is the product of water density, volumetric flow rate of water, water's specific heat capacity and temperature difference in T_{inlet} and T_{outlet}. Volumetric flow rate of water is measured in the energy meter and its average value is 0,5 m^3/h. So far there is no confirmation if this value for volumetric flow rate of water is correct. The reason for this is that the volumetric flow sensor is mounted inside the hose and there is no information available regarding the sensor type. In Hydro Set software, however, the value for the volumetric flow rate is shown in the unit m^3/h and the average value for it is 0.5 m^3/h. Hence, the volumetric flow rate is not used in the calculation of heat dissipated during heating and cooling. Instead, heat dissipation is calculated using the estimated volume of water between the two thermometers, and that volume includes the capacity of water inside the air cooling system, water in the rubber hose and water in the water pump. Air cooling system holds 2.9 liter of water, the water in the hose of 1 meter is approximated to be 200 ml, while volume in the water pump is assumed to be 36 ml. The length of water pump is 180 mm and it is assumed that both the hose and water pump has the same inner diameter of 16 mm. Thus, the total volume of water between the two thermometers is 3.236 liter. Heat is dissipated in the air cooling system and the drop in temperature between the two thermometers indicates this heat loss. In the calculation below, the temperatures are calculated based on the approximated solutions for heating and cooling. Density of water ϱ and specific heat capacity of water c_w are temperature dependent, but for simplification reason their values are held as a constant for the calculation of heat dissipated from the air cooling system. Figure 24 illustrates the cumulative amount of heat dissipated when the water heater is turned on. The unit kWh for energy equals to 3.6 MJ of energy. Heating starts at room temperature and stops when T_{oulet} reaches 80ºC.

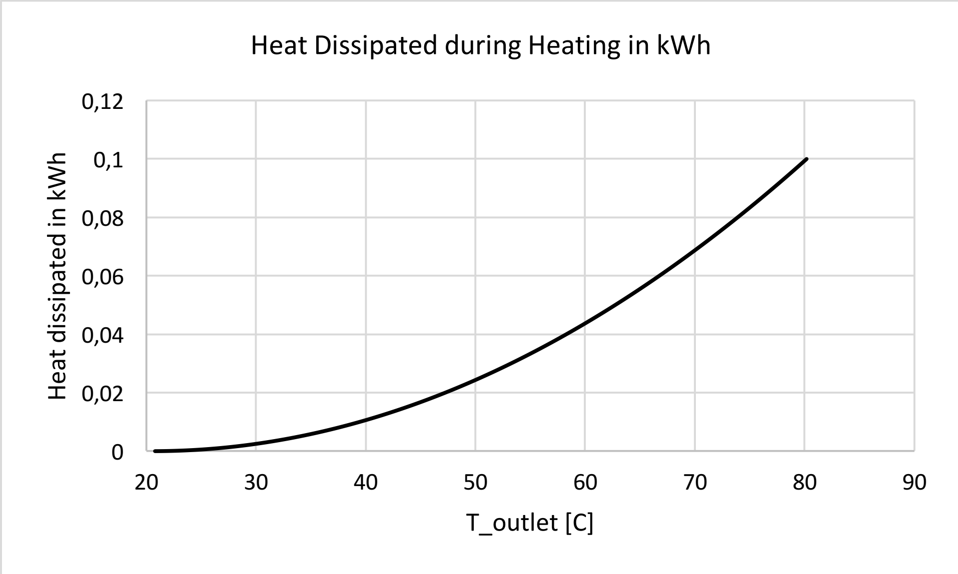

Figure 24. Calculated heat gained in T_outlet using the measured volumetric flow rate of water, kWh

Using the approximated solution for heating, water temperature is calculated and extrapolated to 80ºC for heating. It takes 2 hours and 22 minutes to heat the water from 20.8ºC to 80ºC and the amount of electrical energy supplied to the water heater is 4.25 kWh according to equation (7). As seen in Figure 24, 0.1 kWh is dissipated through the air cooling system alone during heating. As the value for total volume between the two thermometers are approximated, this calculation serves only as a basis to calculate the heat loss during heating.

The exact amount of water in the water heater system is not known. However, a rough estimation can be made based on the water heater capacity, air cooling system's water capacity and length of rubber hose. The water heater has a capacity of 29 liters or $0.029 m^3$, air cooling system allows 2.9 liters of water to flow within it and the total length of rubber hose is 268 cm. The inner diameter of the rubber hose is 16 mm which makes the total volume of rubber hose 0.54 liter or $5.4 x 10^{-4} m^{3.}$ According to this rough estimation, the water heater system has a total volume of $0.032 m^3$, which is calculated using the equation (20) below.

$$V_{hose} = l * \frac{\pi * d_i^2}{4} \tag{20}$$

A further calculation in (6) using this estimated volume of water heater system shows that 2.2 kWh of energy is actually gained to raise the water temperature in T_{outlet} from 20.8ºC to 80ºC. This deviates from the supplied electrical energy and calculated heat loss during heating. This can be explained in the following: in the calculation, water density and specific heat capacity of water is always held constant. These values in real life are a function of temperature, meaning they depend on the water temperature. Generally, the hotter the temperature, the lighter the water density becomes and the higher the specific heat capacity of water becomes. The changes are in the range of 3% and 1% of the default constant value used in the calculation, which is 998.04 kg/m^3 and 4184 J/kg K.

Meanwhile, the cooling time from 80ºC to 60ºC takes about 4 hours and 40 minutes according to the approximated solution. Using the equation in (6) and the estimated total volume in water heater, 0.74 kWh of heat energy is released.

In conclusion, heating the water takes 2 hours to reach 80ºC. The water temperature drops to 60ºC in 4 hours and 40 minutes. To heat the water back to 80ºC requires only 48 minutes using the water heater with a rated power of 1.8 kW. In Figure 25 an example of heating and cooling during a day is shown. At the start, water temperature is heated until 80ºC, which could represent a full State of Charge (SOC) or 100% SOC. Since it takes 2 and a half hours to reach this state, this can take place when there is a surplus of power production from PV or when the electricity price is low. Also, the electrical power needed to increase the SOC from 0% to 100% in this case is 4.5 kWh. For cooling, a drop to 67% SOC will occur after around 5 hours. This period of time could be peak hour. This 40% decrease of SOC is equivalent of 0.74 kWh of available heat output in the water heater system using the equation (6). Additionally, a drop of SOC from 100% to 0% will take 22 hours and a total of 2.23 kWh of heat energy is dissipated to the room. While in theory, charging the water heater from 0% to 100% will require 4.5 kWh of electrical energy, the heat dissipated is only 2.23 kWh. The rest of the energy is transferred to the surrounding by conduction through the wall and insulation layer, valves, hoses, connectors and measurement sensors such as thermometers and volumetric water flow rate. This indicates that air cooling system is not the only heat sink in the water heater system.

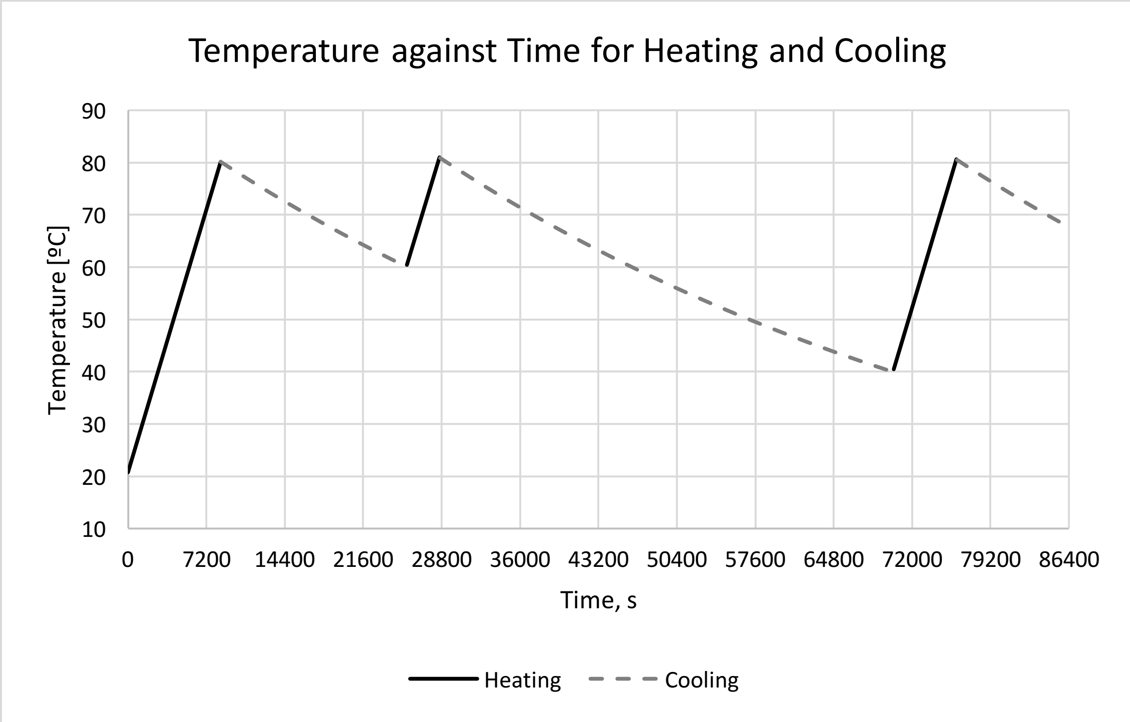

Figure 25. Temperature and time for heating and cooling

5.6 Integration to HEMS

HEMS is a software that aims to control and manage power production, consumption and storage at household level. Right now HEMS is based on the production following algorithm that is developed in the master thesis (Esner, 2014). It calculates the heat demand based on weather profile, estimates power production from PV panels and schedules the time to turn on and off the electric water boiler, electric heater and radiator. In this section, the integration of the approximated solution for both thermometers in heating and cooling into production following algorithm will be discussed.

The production following algorithm uses 290 liters of water boiler, 4 kW of radiator and 6 kW of electric heater provide the heat demand of a 144 m^2 size house. While the water heater in the house has a capacity of 29 liters, the heat output from this water heater is smaller than the one used in production following algorithm. The algorithm estimates the heat demand of the house based on outdoor temperature and the schedules the time to switch on water boiler, radiator and electric heater so that their heat output could match the heat demand. Meanwhile, the equations or approximated solutions uses time to calculate the temperature of water at the positions where the thermometers are installed.

There are several points in the production following algorithm that would have to be redesigned in order to allow the integration of water heater system in HEMS. Firstly, the heat output from the water heater system is obviously smaller than the water boiler used in production following algorithm. There are two solutions to this; the heat demand estimation of the house should be scaled down by using a smaller house or the heat output should be compensated by other means of heating, such as increasing the number of radiators or electric heater. Secondly, the heating components in the algorithm is scheduled or programmed when to be turned on. The scheduling does not work with the equations as the sole purpose of the equation is to use time to calculate the temperatures for both thermometers. These calculated temperatures would represent the measured temperature had the communication link between water heater system and HEMS computer existed. Scheduling is done based on the calculation of heat demand the boiler is able to output. This calculation is based on the parameters such as water volume and boiler's rated power. There is a proposed solution and that is to redesign the way scheduling works. Scheduling should include real time water temperature inputs and calculate the heat output based on the temperatures reading instead of using the static parameters of a water boiler for heat estimation. Thirdly, a central control that could control the turning on and off of water heater based on the water temperature should be implemented. This central control could read actual temperature and make decision based on the weather forecast and electricity price.

The central control should also be able to calculate the heat demand needed in the house. This will require the information of such as thermal resistance of the house and outdoor temperature so that the heat loss to the surrounding can be calculated. The example of heat demand calculation based on the temperature readings provides an insight of how the central control could maintain the heat output in a house.

6. CONCLUSION

Water heater system is added recently to the microgrid laboratory. It serves as a controllable load whose switch-on time can be controlled by HEMS. The software HEMS stands for Home Energy Management System and its goal is to control the load demand in a household by balancing the power production from PV, battery storage and controllable loads such as water heater system.

The thesis investigated the communication protocol used by the energy meter in water heater system. The energy meter is a metering device that collects water temperatures and volumetric flow rate of water from the sensors installed on the water heater system. Basic calculation such as energy consumption and billing information can be done within the energy meter. The major challenge here would be to enable the energy meter's communication with external computer. In this case, the communication with HEMS is highly desirable so that water temperatures of the heater could be known by HEMS. This would help to control the water heater system through a central control unit. The communication protocol used by the energy meter is M-Bus protocol or Meter-Bus protocol. It uses bus topology to send signals between the master and slaves reliably and cost-effectively. M-Bus supports up to 250 slaves and a master. The slaves could be any metering device for water, electricity or gas. In this case, the energy meter is a slave while the external computer is a master. Communication is started when master sends inquiring signals to targeted slave which is identifiable with a physical address. Targeted slave responds to the master if it successfully receives the signal by sending commands documented in (Ziegler, 1992). This thesis did not focus on building the communication between the energy meter and external computer and this would be the future development in microgrid laboratory.

The thesis analyzed the relation between time and temperature for heating and cooling in the water heater system and this relation could be approximated using linear regression. Heating can be approximated using linear least squares fitting while cooling can be approximated using exponential least squares fitting. The water temperatures at both thermometers for heating and cooling can be calculated or reproduced using these approximated solutions. This is possible as the water heater system is a closed-loop system. There is neither water source or sink in the system. In the long run, impurities inside the water heater system could be formed due to oxidation of resistive heating rode inside the water heater and this could affect the specific heat capacity of the water and thus the heating and cooling time measured in the experiments.

In the water heater system, it takes 70 minutes for heating until 56ºC, which is the maximum temperature due to overheating protection from the thermostat. The hot water takes about 15 hours to cool down to room temperature in the laboratory at 20.8ºC. Extrapolation of the water temperature for heating until 80ºC is done with the help of approximated solution. A SOC of 100% can be said when the water temperature reaches 80ºC and 0% when it is at room temperature. Charging the SOC from 0% to 100% requires 4 hours of time and discharging requires 22 hours. A theoretical 7.2 kWh of heat energy is available by discharging the water heater from 100% to 0% as it is the amount of electrical energy supplied by the water heater. In contrast, in the calculation of heat dissipation using the difference of water temperature at T_{outlet} and T_{inlet}, 2.23 kWh of heat energy is calculated to be released to the surrounding. It can be seen that not all the electrical energy is converted to the heat energy dissipated through the air cooling system and most of it is lost to the surrounding by heat transfer through conduction in hoses, water heater insulation as well as the measurement sensors. The water heater system is not a perfectly insulated system where the only heat sink is the air cooling system. There are other heat sinks as well such as the valves, hoses, connectors, water pump, walls and insulation layer of the water heater and measurement sensor. However, the rate of heat loss depends on the difference of the water temperature with the surrounding ambient temperature. The higher this difference is, the faster the rate of heat loss is. This property is seen in the exponential decrease of water temperature during cooling.

There are several factors that have been discussed in the thesis to have an influence in determining the time when water heater should be switched on. The first factor is the variation of outdoor temperature in different days and nights throughout the year, which as a result affects the heat demand a house needed. Secondly, the availability of direct irradiance from the sun or the position of the sun in the horizon affects the amount of power production from PV. Thirdly, the hourly electricity price from Elspot day-ahead market which is determined by the supply from producers and demand from consumers.

6.1 Future work

This section encloses the future work that is related to the development of microgrid laboratory. First of all, the communication between the energy meter and HEMS computer would enable autonomous data exchange between these two components and a central control within HEMS could be further developed. This central control could receive inputs from PV invertor regarding the active and reactive power as well as maximum power point of the PV invertor. The control could also read the water temperature from the energy meter and decides when to turn it on based on information such as PV production, electricity price and heat demand required in a house. A universal gateway which translates different communication protocols such as M-Bus and Modbus RTU could also be designed as an interface before HEMS. This would convert different communication protocols to a unified protocol such as IEC61850. Moreover, if the production following algorithm were to be used as HEMS, the algorithm should be modified in a way that it can read the water temperature from the energy meter.

The limitation and flexibility of water heater to be a controllable load in conjunction with a PV panel could be investigated by varying the uncertainty of PV estimation. These input could be fed into an optimization algorithm based on Matlab. Last but not least, calibration of the thermometers and volumetric flow rate sensor could reduce the error and improve the accuracy in measurement.

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